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We are honoured to present this special edition of the *Interdisciplinary Journal of Papua New Guinea University of Technology (IJPNGUoT)* in celebration of the **Golden Jubilee of Papua New Guinea's Independence**. This historic milestone marks fifty years of national progress and offers a profound opportunity to reflect on the remarkable advancements in science, engineering, technology, innovation, and entrepreneurship that have shaped our nation's journey.

This commemorative issue brings together a diverse collection of scholarly contributions—not only from Papua New Guinea but also from international researchers—underscoring the global relevance and collaborative spirit of our academic community. With deep pride in our nation's achievements, we invited original research papers, review articles, short communications, and case studies that illuminate groundbreaking developments, address contemporary challenges, and propose visionary pathways for the future.

The special issue is designed to foster interdisciplinary dialogue and contribute meaningfully to the pursuit of global sustainability goals. It offers a comprehensive overview of current research, showcases cutting-edge technological innovations, and outlines strategic directions for the advancement of science and technology in service of sustainable development. Topics span national development priorities, international issues pertinent to PNG, business and economic prospects, sociocultural dynamics, and more.
We are grateful for the overwhelming response from scholars and researchers, and we have carefully curated the most impactful manuscripts based on the thoughtful recommendations of our esteemed reviewers. Their rigorous evaluations have ensured the academic integrity and relevance of this publication.
Looking ahead, IJPNGUoT remains committed to supporting the socio-economic development of Papua New Guinea, the Pacific region, and the global community by publishing high-quality interdisciplinary research across Pure and Applied Sciences, Engineering and Technology, Smart Built Environments, Humanities, and Sustainable Agricultural Services.

On this momentous occasion, we extend our heartfelt appreciation to all contributors, reviewers, editorial collaborators and the university press whose dedication has made this special issue possible. May it serve as both a tribute to our past and a beacon for our future.

PNGUoT at 50 Years of Independence: A Vice Chancellor's Vision for a World-Class University

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Abstract: As Papua New Guinea marks fifty years of independence, the role of higher education in national development must be redefined and strengthened. This manuscript reflects on the philosophy, vision, and institutional reforms that have guided the Papua New Guinea University of Technology (PNGUoT) over the past five years. It articulates the belief that universities are sovereign institutions of knowledge, entrusted with authority to generate, transfer, and apply science and technology to uplift livelihoods. The paper highlights milestones achieved under the current leadership, including full accreditation of five engineering programs under the Washington Accord, establishment of international collaborations, creation of the Office of Strategic Internationalization (OSI), and mobilization of industry partnerships. Ultimately, it argues that PNGUoT must be a driver of societal transformation by ensuring that higher standards of education directly translate to higher standards of living for the people of Papua New Guinea.

Keywords: PNGUoT, world-class university, sovereignty, accreditation, Washington Accord, internationalization, industry partnerships, Pacific Islands, sustainable development.

1. INTRODUCTION: UNIVERSITIES AND THE QUESTION OF SOVEREIGNTY

In 2018, as I prepared to apply for the role of Vice Chancellor of PNGUoT, I was compelled to ask a fundamental question: *What is the real role of the University in society?* My conclusion was unequivocal—the University must be the custodian of science and technology, a repository of knowledge to be imparted to young men and women, and a generator of research and innovation to improve livelihoods.

I articulated this philosophy using the term **sovereignty**, defined as the authority of a nation to govern itself. The root word for "authority" is *author*, and it is the authors—of theses, publications, project reports, and consultancies—who reside within universities. Professors, researchers, and scholars collectively form the intellectual authority of a nation. Thus, universities are not merely training institutions; they are sovereign bodies of knowledge that must inform and influence governance with scientific evidence and guide national development.

This philosophy led me to articulate three objectives for PNGUoT:

1. Students must graduate with world-class degrees.
2. Professors must conduct solution-oriented research for industry and community, attracting sustainable funding from both.
3. Technology transfer must extend into projects that improve rural livelihoods.

I have consistently emphasized in public forums that Port Moresby and Lae are not the entirety of Papua New Guinea. With 85% of our population living in rural communities, the true measure of a university's success must be its impact on improving the living standards of the rural majority. In developed countries, the leadership role of world-class universities is directly linked to higher standards of living. PNGUoT must assume this same mantle of leadership.

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2. INSTITUTIONAL TRANSFORMATION AND ACCREDITATION MILESTONES

Upon my appointment as Vice Chancellor in April 2019, PNGUoT launched a **Strategic Plan** with a vision to grow world-class technocrats for the real world. A major challenge lay in securing accreditation for our engineering programs, which required upgrading facilities, procuring equipment, and strengthening staff capacity. A turning point was the termination of the catering contract with iPi Ltd and the insourcing of services. This bold decision resulted in annual savings of K8 million, which were strategically redirected into accreditation activities. As a result, **Engineers Australia awarded full Washington Accord accreditation to five engineering programs in December 2024**—a historic milestone that placed PNGUoT on the global academic stage.

This achievement was only possible through decisive leadership, prudent financial reforms, and the support of visionary Council members. It has elevated PNGUoT's profile, enabling our graduates to compete globally while reinforcing our institutional credibility.

3. INTERNATIONAL COLLABORATIONS AND THE ROAD TO GLOBAL STANDARDS

I have always believed that collaboration with world-class universities is central to PNGUoT's growth. Exposure to global practices equips students and staff with international perspectives, ensures graduates are globally mobile, and enables professors to contribute to cutting-edge research.

In 2023, Associate Professor George Varughese of the University of New South Wales (UNSW) visited PNGUoT as part of UNSW's mission to enhance global rankings through societal impact, measured by the UN Sustainable Development Goals (SDGs). His visit catalyzed agreements for collaboration, strengthening PNGUoT's research engagement in climate change, agriculture, energy, and other critical fields.

That same year, at the Pacific Islands Universities Research Network (PIURN) meeting in the Cook Islands, I successfully bid for PNGUoT to host the 2025 PIURN Conference. This positioned our University as a hub for Pacific knowledge exchange.

Recognizing the increasing demand for coordination of these partnerships, I proposed the establishment of the **Office of Strategic Internationalization (OSI)**. Although initially rejected, the motion was eventually passed with strong advocacy from Councilor Hemetsberger and financial support from Ok Tedi Mining Limited (OTML). The OSI has since become the driver of our global collaborations.

4. RESEARCH, INDUSTRY PARTNERSHIPS, AND THE 2025 PIURN CONFERENCE

By 2025, PNGUoT's international profile had expanded significantly. Following the accreditation celebrations in June, PNGUoT hosted the **PIURN Conference from July 1–3, 2025**, which brought together Pacific researchers, industry partners, and international collaborators, notably from UNSW.

Key research collaborations emerged in areas vital to the Pacific, including climate change, renewable energy, food security, sea-level rise, urbanization, transport engineering, and environmental conservation. The **United Nations Global Pulse Program** committed to supporting PNGUoT-led sea-level rise studies.

Crucially, industry stakeholders rallied behind PNGUoT. Companies such as OTML, Kumul Petroleum Holdings Ltd (KPHL), Kumul Minerals Holdings Ltd (KMHL), Wafi-Golpu Joint Venture, and Dataco Ltd became financial patrons of OSI, demonstrating their confidence in PNGUoT's role as an engine of innovation and development.

5. CONCLUSION: TOWARDS A WORLD-CLASS UNIVERSITY WITH SOCIETAL IMPACT

Reflecting on these milestones, I return to the conviction that ignited my vision in 2018: universities must translate higher standards of education into higher standards of living. For PNGUoT, this means:

- Benchmarking academic programs to international standards.
- Expanding collaborative research to address national and regional challenges.
- Strengthening industry partnerships for solution-based research.
- Enhancing community outreach to improve rural livelihoods.

Through the OSI, strategic reforms, and partnerships, PNGUoT is increasingly recognized as a world-class institution. The journey is ongoing, but the direction is clear—PNG's future prosperity is inseparable from the strength of its universities. PNGUoT must continue to lead, innovate, and serve, ensuring that the knowledge we generate transforms the lives of our people.

Redefining Papua New Guinea's Law-and-Order Path: Learning from the Past and Forging a New Approach in the 50th Year of Independence

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Abstract: This paper analyzes Papua New Guinea's (PNG) law-and-order challenges since independence in 1975 and proposes strategies for sustainable improvements as the nation marks its 50th year of independence. PNG faces complex and diverse issues, including corruption, transnational crime, ethnic conflicts, property crimes, and violent crimes, including serious abuse of human rights, which are exacerbated by weak institutions, poverty, unemployment, and other structural socio-economic factors. Historically, state responses have been reactive and crisis-driven, often failing to address underlying structural weaknesses and socio-economic inequalities. Drawing on literature, the study emphasizes the importance of good governance, responsible leadership, and active citizen engagement in addressing crime. To achieve lasting peace and security, PNG must prioritize its people, strengthen governance and the criminal justice system, eliminate corruption and illegal firearms, reform education to enhance employment and entrepreneurial opportunities, and leverage technology for accountability and effective law enforcement. The paper presents PNG's 50-year law-and-order strategic agenda (2025–2075) as a key roadmap for building a safe, equitable, and resilient society.

Keywords: Redefining, law-and-order, forging, independence, leadership, and crisis-driven

1. INTRODUCTION

As Papua New Guinea (PNG) marks 50 years of independence, the country must seriously reflect on its journey as an independent state. The territory now known as PNG was formally colonized in 1884 (Waiko, 1986) and existed under colonial rule for 90 years before gaining independence on 16th September 1975. Independence was never intended to be a pretext for continuing colonial administration. However, in the absence of a formal traditional institutional structure, the country had no choice but to adopt Western colonial systems to manage its affairs and governance (Sali, 1996).

Since the values and practices of colonial institutions were not rooted in Papua New Guinean culture, the transition to parliamentary democracy and bureaucratic administration has been challenging. As we continue to adapt to these foreign systems, issues remain regarding our effective integration of Western political and administrative models.

Before PNG gained independence, its law-and-order system was primarily shaped by traditional justice mechanisms, colonial governance, and the gradual transition to self-rule. Traditionally, PNG's diverse societies-maintained order through customary laws, where village elders, chiefs, and community leaders played key roles in resolving conflicts. These systems emphasized reconciliation, compensation, and communal harmony rather than punitive justice (Goddard, 2009). Disputes were typically settled through mediation, often involving compensation payments in the form of shells, pigs, or other valuable goods. This indigenous approach to justice was well-suited to PNG's tribal society, where maintaining social cohesion, peace and was a priority (Dinnen, 1997).

The arrival of colonial rule in the late 19th and early 20th centuries introduced a Western-style legal ar law enforcement system, which often conflicted with traditional customs. Under German and later Australia administration, formal policing structures were established, such as the Armed Native Constabulary in the la 19th century, which later became the Royal Papua New Guinea Constabulary (Sinclair, 1985). Colonial la enforcement aimed to maintain order, particularly to protect European economic interests, but often struggled

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effectively control rural areas, where traditional justice remained dominant. The introduction of codified laws and the court system centralized authority away from local communities, creating tensions between indigenous practices and the imposed legal framework (Dinnen, 2001).

As PNG moved towards independence, the challenge of merging traditional and modern law enforcement became more apparent. The establishment of the House of Assembly in 1964 and self-government in 1973 marked significant steps towards legal and political autonomy (Premdas, 1985). However, law-and-order challenges persisted, particularly in balancing state-imposed justice with customary law. Upon gaining independence in 1975, PNG inherited a hybrid system, where formal legal institutions coexisted with traditional dispute-resolution mechanisms. This dual system remains relevant today, as PNG continues to grapple with law-and-order issues stemming from historical governance structures, socio-economic inequalities, and the complexities of its diverse legal traditions (Goddard, 2009).

Law-and-order is fundamental to PNG's social and economic development, as stability and security create an environment conducive to investment, governance, and community well-being. Persistent law-and-order challenges, including crime, tribal conflicts, and weak enforcement mechanisms, have hindered economic growth, deterred foreign investment, and strained social cohesion. As PNG enters its next 50 years of independence, rethinking the approach to law-and-order is crucial to promoting a safer, more prosperous nation. A renewed strategy must address both systemic weaknesses in law enforcement and the deeper social attitudes that contribute to disorder. By integrating effective governance, community participation, and modern policing strategies, PNG can lay a stronger foundation for sustainable development, ensuring that future generations inherit a nation defined by stability, justice, and opportunity.

Law-and-order in PNG is not solely a matter of systems, policies, and enforcement mechanisms—it is fundamentally an attitude issue that extends from ordinary citizens to law enforcement officials and political leaders. Since gaining independence in 1975, PNG has faced persistent law-and order challenges, struggling to balance traditional justice systems with modern legal frameworks. Over the past 50 years, weak enforcement, political interference, corruption, and societal attitudes toward crime have contributed to ongoing instability. While efforts have been made to strengthen policing and judicial processes, these have often been undermined by a lack of urgency, political will, and commitment from those in authority. Now, as PNG marks its 50th year of independence, it is critical to redefine its approach to law-and-order with a renewed focus on accountability, ethical leadership, and community-driven solutions. Law enforcement agencies and political leaders must not only have the right attitude but also demonstrate urgency and willpower in addressing these challenges. Impartial law enforcement, stronger anti-corruption measures, and a shift in societal mindset toward responsibility and collective security are essential.

Therefore, it is essential to critically examine how far we have come, assess how we as a nation are addressing these challenges, and forge a new approach across all areas of socio-economic development, politics, the environment, science, engineering, and technology. In this context, this paper aims to redefine the country's law-and-order path by learning from the past and charting a new course in this 50th Year of Independence.

2. HISTORICAL CONTEXT OF LAW-AND-ORDER IN PNG

Before PNG gained independence in 1975, law-and-order issues were shaped significantly by the colonial justice system imposed by the Australian administration. This system, in place since 1884, focused more on maintaining control and discipline over the indigenous population than on fostering a just or culturally sensitive legal structure. Justice was administered through a punitive and militarized approach, emphasizing order and obedience rather than fairness and community resolution. Limited attention was given to creating a balanced system that could respond to the social and cultural realities of Papua New Guinean communities. Morauta (1986) pointed out that the seeds of the current law-and-order problems were sown well before independence, due to a lack of meaningful development of a justice system that resonated with indigenous values and customs.

The colonial administration's failure to recognize and incorporate traditional justice mechanisms created a disconnect between the imposed legal structures and the lived experiences of most Papua New Guineans. In rural areas, where access to colonial justice institutions was limited or non-existent, people continued to rely on customary methods to resolve disputes and maintain peace. However, these practices were often seen as

illegitimate or inferior by the colonial authorities. As a result, indigenous communities found themselves caught between two systems—traditional norms that governed everyday life and a foreign legal system that neither understood nor respected their ways of resolving conflicts (Paliwala, 1982)[1]. This duality created legal confusion, weakened traditional authority, and contributed to the erosion of communal harmony.

Despite the dominance of colonial structures, many communities maintained their traditional methods of resolving disputes and managing law-and-order. These methods, based on consensus, restitution, and restoration of relationships, were deeply embedded in Papua New Guinean societies (Sali, 1996). Leaders such as village chiefs, elders, and big men played central roles in these processes, using mediation and dialogue rather than punishment to resolve issues. While these systems were not formally recognized by the colonial government, they remained effective in maintaining peace at the local level (ibid).

The current challenges in law-and-order in PNG are largely rooted in the colonial administration's failure to formulate laws and policies that aligned with the country's traditional social regulatory systems (Narokobi, 1983). During the colonial period, the justice system was not designed to serve or reflect the values of indigenous communities but was instead used as a tool to advance the colonialists' political, economic, and religious agendas, along with their own cultural beliefs and practices (Turner, 1990). This imposition undermined existing systems of customary governance and justice, stripping Papua New Guineans of their unwritten laws, traditional social structures, communal authority systems, and ultimately their pride, dignity, and self-respect (Narokobi, 1983, in Clifford et al., 1984:110). As a result, the legacy of colonial rule has contributed significantly to the fragmented and often ineffective state of law-and-order experienced in the country today.

3. THE POST-INDEPENDENCE DEVELOPMENT OF LAW-AND-ORDER IN PNG

Concerns around law-and-order in PNG did not emerge suddenly but were part of ongoing debates throughout the colonial period and into the first decade (1975-1985) of independence. As Clifford et al. (1984:1) note, "Through the entire colonial period and the full decade of independence, the problem of 'law-and-order' has been under active consideration by government and people alike." Upon leading PNG to independence in 1975, the late Grand Chief Sir Michael Somare inherited a fragile internal security landscape, with rising crime largely attributed to loosely organized groups of unemployed urban youth known as raskol gangs[2]. These gangs rapidly gained

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[1] When administration of both New Guinea and Papua came under the charge of the Australians after the First World War in 1914, they extended their paternalistic technique which they have been using in the southern part of the island of New Guinea since 1884 under their control. "Under the Australian administration of both Papua and New Guinea, the lower court system was constituted by the Courts for the Native Matters in Papua and the Courts for the Native Affairs in New Guinea" (Downs, 1980:148 in Banks, 1993:18). These courts were alien and external to the indigenous people but regulated their way of lives. 'The traditional leadership became subordinate to the authority of the kiap" (Paliwala, 1982: 193). This official regularity system sometimes failed to maintain law-and-order as Rowley noted: The introduction of rule of law at once involves the government in the attempt to administer justice, which proves illusive and difficult in the shadow world between two cultures (1965:76).

[2] See Sali, (2015) who captured that: "raskols in the PNG context are young men, usually in groups (Luker & Monsell-Davis, 2010).), who operate mainly in the larger cities, particularly in Port Moresby and Lae to commit crime against persons and properties. They are notoriously known for engaging merciless crimes like murder, rape, robbery, and armed hold-ups, which are characterized as violent and serious acts of brutality against humanity. Raskols have become one of the most prominent features of the urban landscape and one of the most significant issues facing the country at present (Harper, 1998, p.31). The extant literature reveals that raskols began to operate criminal activities in Port Moresby in the late 1950s and early 1960s (Nibbrig, 1992). It was during this time when the term raskol was introduced and used by expatriates, and then gained predominance and was later appropriated by the gangs themselves (Harris, 1988). These early raskols of Port Moresby were initially a by-product of urbanization process in parallel with the removal of the colonial control of the indigenous population (Oram, 1976). With the removal of internal migration controls after Independence in 1975, more indigenous people moved into Port Moresby and created illegal settlements. Along other freedoms, the indigenous population also gained access to alcohol, which was previously restricted to the colonial whites only (Oram, 1976). In the 1960s, illegal offences committed by raskols, who were then mainly uneducated indigenous people, were simply petty thefts and acting disorderly in public places after drinking alcohol. Their illegal activities were

notoriety for violent acts such as murder, rape, armed robbery, and other brutal crimes (Sali, 2014). In response, Somare swiftly initiated a series of forums and research efforts to establish a national response to crime, enlisting both international and local expertise. Among the foundational reports consulted were the Derham Report (1960), the Committee on Tribal Fighting in the Highlands (PNG, 1973), and the Peace and Good Order Committee Report (Papua New Guinea, 1974), alongside expert assessments from the Australian Institute of Criminology (Biles, 1976; Clifford, 1976). These reports laid the groundwork for reforms in policing, judicial administration, and legal frameworks, including the Intergroup Fighting Act (1977), which empowered the state to intervene in tribal conflicts (Mapusia, 1986). Additionally, the National Youth Movement was launched to mobilize young people and redirect them into productive socio-economic activities.

Despite these early efforts, crime rates escalated, and public anxiety intensified (Clifford et al., 1984). In response, the government commissioned a major two-volume study titled Law-and-Order in PNG—commonly known as the Clifford Report (1984). This comprehensive report reiterated concerns first raised in the late 1970s, highlighting persistent structural weaknesses in the law-and-justice sector. It emphasized the government's growing frustration and concern over escalating violence, especially in urban centers like Port Moresby and Lae, where raskol activity, ethnic clashes, and violent crimes were increasingly reported in the media. Tribal fighting also remained a constant challenge in parts of the Highlands. Pressured by both domestic and international expectations, the government resorted to short-term, reactive measures that yielded limited long-term success. As Dinnen (2001) observes, PNG continued to rely on ad hoc, heavy-handed approaches that often-provoked retaliation and further exacerbated law-and-order problems, rather than resolving their root causes.

As we celebrate 50 years of independence, it is vital to acknowledge that throughout this period, law-and-order challenges have persisted and even worsened. Criminal and violent social behavior has escalated, facilitated by the increasing flow of firearms, as highlighted by retired Major-General Jerry Singirok, who chaired the Guns Control Committee and emphasized the urgent need to eliminate weapons and reduce centralized power to restore public safety (Post-Courier, 2023). At the same time, the law and justice sector has struggled to respond, characterized by weak institutional capacity and fragmented oversight, with scholars noting that merely strengthening individual agencies is insufficient without a broader, integrated sector-wide strategy (Dinnen, 2002). Furthermore, societal violence has been exacerbated by weak enforcement, growing impunity, and cultural dynamics that traditional criminal justice approaches fail to address (Dinnen & Allen, 2018). We must therefore redefine and reform our current practices—transforming both policy design and implementation to build stronger, more adaptive systems that truly protect citizens.

4. CONTEMPORARY LAW-AND-ORDER CHALLENGES IN PNG

PNG has faced continued law-and-order challenges, ranging from corruption and white-collar crimes to transnational crime, ethnic conflicts, property-related offenses, and violent crimes against individuals. Recent incidents such as murder cases, a mass prison breakout, and clashes between police and defense personnel have further highlighted the country's ongoing struggle with serious crime (The National, 2025). In the absence of detailed crime statistics, descriptive accounts and theoretical perspectives continue to provide important insights into the underlying drivers and consequences of these crimes. Some contemporary law and order challenges are highlighted below:

4.1 White-Collar Crime and Corruption

White-collar crime, first defined by Sutherland (1940; 1949), involves crimes committed by individuals of high social status during the course of their occupations, including fraud, bribery, money laundering, and embezzlement. Globally prevalent (Allen & Overy, 2015), these crimes are often motivated by opportunity,

also restricted in the settlements. However, in the 1970s the raskols, who by this time recruited educated indigenous elites into their ranks, moved into more affluent neighbourhoods that yielded more profitable 'returns' from crime (Harris, 1988).

arrogance, entitlement, or competitiveness (Bucy, Formby, Raspanti & Rooney, 2012). Their impacts extend beyond financial damage to moral and social consequences (Meier & Short, 1982).

In PNG, white-collar crime is synonymous with corruption (Sause, 1992) and is widespread across politics, the public service, and private industries such as logging and banking (Pitts, 2001). Transparency International's 2015 Corruption Perceptions Index ranked PNG 145 out of 178 nations, confirming corruption as a systemic and systematic issue (Transparency International, 2015; Yuangua, 2001; Sali, 2014). Politicians, including senior ministers and governors, have been convicted of misappropriating public funds (Dennin, 1993a; Pokiton, 2016). Similar offenses by bureaucrats and business figures, such as the theft of millions of kina from the state (Paso, 2015; Tien, 2015), reinforce the view that corruption is normalized. Weak state institutions, combined with greed and cultural obligations, have created an enabling environment for corruption to flourish (Pitts, 2001).

4.2 Transnational Crime

Transnational crimes—defined as criminal acts involving two or more nation-states (Bossard, 1990; Hensaw, 2008)—include smuggling, contraband trading, and illicit services such as money laundering and human trafficking (Reuter & Petrie, 1999). Advances in globalization, liberalized economies, and technology have made such crimes adaptable and resilient (Shelly, 2004).

In PNG, weak law enforcement, corruption, and porous borders create fertile conditions for these crimes (McCusker, 2006; Mitna, 2014). Firearms and drugs are exchanged across the PNG–Australia and PNG–Indonesia borders, contributing to internal violence (Forbes, 2014; Sakai, 2012). Human trafficking has also emerged as a major concern, with foreign and local women forced into sex work, and men subjected to bonded labor in industries such as mining and logging (US Department of State, 2010; Sakai, 2012; Forbes, 2014). These developments demonstrate how transnational crime compounds PNG's already fragile governance landscape.

4.3 Ethnic Conflicts

PNG's extreme cultural diversity has long contributed to ethnic tensions and conflict (Oram, 1976; Turner, 1990). Such conflicts, often violent, threaten national unity (Ukaha, 2014; Radio NZ, 2015). Ethnic disputes arise from bloodlines, tribal affiliations, language, and regional identities (Chandra, 2012; Cordell & Wolf, 2010). Immediate consequences include property destruction, injuries, and deaths, while long-term trauma undermines stability.

Scholars explain ethnic conflict through primordialism, which emphasizes birth-based group identity and deep allegiance (Isajiw, 1993; Perez & Hirschman, 2009), and instrumentalism, where elites mobilize ethnicity for political or economic gain (Collier & Hoeffler, 2002; Chandra, 2004). In PNG, instrumentalist mobilization was evident during the Bougainville Crisis (1988–1998), where ethnic divisions fueled a decade-long conflict with devastating social and economic consequences (Dorney, 2000).

4.4 Property Crime

Property crimes in PNG—robbery, burglary, theft, arson, vandalism, and embezzlement—are widespread and often linked to socio-economic hardship. Strain theory (Durkheim, 1933; Merton, 1957) suggests individuals facing blocked opportunities may turn to crime to achieve material goals. Merton's concept of "anomie," or imbalance between aspirations and means, resonates with PNG's high rates of theft and robbery, especially among unemployed youth (Clifford et al., 1984; O'Collins, 1984).

Agnew's (1992) general strain theory highlights emotional stress as a driver of destructive crimes such as arson and vandalism. The 2016 student riots at the University of PNG and PNG University of Technology, which saw the burning of buildings and vehicles, reflect this pattern (Sali, 2016). International assessments, including those by the US Department of State, rank PNG among the highest in the world for property crime risks (USDS, 2015; Miamel, 2016a).

4.5 Crimes Against Persons

Crimes against persons—homicide, rape, and assault—are among the most severe in PNG. Willful murder is frequently reported, linked to tribal fighting, robbery, sorcery accusations, and personal disputes (Vuvu, 2016; Gumuno, 2016; Faiparik, 2016; Sali, 2015). Despite its gravity, murder persists at alarming levels.

Rape and sexual violence remain pervasive. Incidents include both rare cases of male victims and widespread attacks on women, such as the widely condemned East Taraka rape of a nurse in Lae (Radio NZ, 2013; Uki, 2010). Cultural normalization of rape, driven by anger, social identity, and sexual gratification, sustains this cycle (Sali, 2013a). Gender-based violence is equally alarming, with reports suggesting up to 67% of PNG women experience abuse (The Guardian, 2016).

Assault—verbal, written, or physical—is also prevalent. Increasingly, cyber-based defamation on social media has emerged, prompting legislative responses (Porau, 2016; The National, 2016). Physical assaults occur in contexts ranging from domestic disputes to public brawls, often leaving both physical and emotional scars (Mera, 2013; Kuku, 2015).

Theoretical perspectives help explain these patterns. Psychological approaches emphasize poor childhood socialization leading to antisocial behavior (Shoemaker, 1990), while sociological explanations highlight poverty, unemployment, and peer influence within disorganized (Agnew, 1992). Both perspectives demonstrate how social and individual forces converge to perpetuate violent crime in PNG.

In short, PNG faces a multi-dimensional crime crisis that spans corruption, transnational crime, ethnic conflict, property offenses, and violent crimes against persons. Weak state institutions, socio-economic hardship, and cultural complexities interact to drive these challenges. Without targeted interventions, crime will remain a continued barrier to PNG's development and national stability going forward.

5. STATE RESPONSES TO LAW-AND-ORDER PROBLEMS

5.1 Colonial Justice Administration

The roots of PNG current law-and-order challenges can be traced back to the colonial period. Morauta (1986:8) observed that "the seeds of today's social and institutional problems were sown well before 1975," reflecting how the Australian administration failed to develop justice systems aligned with indigenous traditions. From 1884 until independence in 1975, the colonial state prioritized stability for its own rule, using punitive and paramilitary measures rather than fostering genuine justice (Paliwala, 1982).

The justice system functioned largely as a mechanism to extend economic, political, and religious control (Turner, 1990). Indigenous governance structures, unwritten laws, and communal systems were marginalized, eroding traditional social regulation and undermining dignity and self-respect (Narokobi, 1983; Clifford et al., 1984). Consequently, PNG's fragile justice framework at independence was a direct legacy of this neglect.

5.2 The First Decade of Independence: 1975–1985

Concerns about law-and-order persisted into the post-independence period. Clifford et al. (1984:1) note that crime was under "active consideration" during both the colonial era and the first decade of independence. With independence in 1975, Sir Michael Somare confronted the rise of "rascal" (raskol) gangs—loosely organized groups of young men engaged in violent crimes such as murder, rape, and armed robbery (Sali, 2014).

In response, Somare commissioned research and policy initiatives. Key reports, including the Derham Report (1960), the 1973 and 1974 peace and order committee reports, and advice from the Australian Institute of Criminology (Biles, 1976; Clifford, 1976), informed early strategies. Legal reforms such as the Intergroup Fighting Act (1977) aimed to curb tribal warfare (Mapusia, 1986), while programs like the National Youth Movement sought to channel youth into productive activities.

Despite these efforts, crime escalated. The Clifford Report (1984) highlighted structural weaknesses in law enforcement and justice institutions and warned of growing violence in urban centers such as Port Moresby

and Lae, alongside tribal fighting in the Highlands. Faced with mounting domestic and international pressure, the government relied on ad hoc interventions that produced limited results, often provoking retaliation and further instability (Dinnen, 2001).

5.3 Crisis-Driven Approaches: 1986–2015

Crime control policies in Papua New Guinea (PNG) between 1986 and 2016 were shaped less by coherent long-term planning than by political expediency. Dinnen (2001:3) observed that crime responses in PNG were largely reactive, with successive governments opting for short-term measures to contain crises rather than building institutional capacity or addressing root causes. This period illustrates how governance challenges, weak institutions, and public pressure pushed leaders into adopting emergency-style interventions aimed at demonstrating control. While such measures occasionally succeeded in suppressing disorder, their inability to deliver sustained outcomes entrenched a cycle of instability and eroded confidence in state legitimacy.

One of the most visible crisis-driven strategies was the repeated declaration of states of emergency in urban centers. Since 1985, governments have frequently imposed curfews and deployed security forces in Port Moresby, Lae, and other hotspots when violence escalated (Dennin, 1993a). The reliance on extraordinary powers gave the impression of decisive action, particularly in moments of heightened public insecurity. For instance, in 2012, a state-backed intervention in Lae succeeded in temporarily restoring calm (Sali, 2014). However, as Harris (1988) pointed out, such operations had limited long-term value because law and order quickly deteriorated once security forces withdrew. These patterns revealed the transient nature of militarized operations, which disrupted criminal activity in the short term but did little to prevent its recurrence.

Crisis-style interventions were also evident in state responses to tribal and ethnic conflicts. The police and, at times, the military were deployed to contain violent clashes in the Highlands and inter-ethnic conflicts in towns. While interventions sometimes halted violence in the immediate sense (Mapusia, 1986), their effectiveness was undermined by excessive use of force and the lack of follow-up strategies. In many instances, the temporary presence of security forces merely postponed further outbreaks. This was evident in the recurrent tensions between Morobe and Highlander groups in Lae between 2011 and 2016, which reignited once police contingents were withdrawn (Okole & Unage, 2011; Ukaha, 2014). These experiences underscored the inability of reactive deployments to resolve underlying disputes or build community-based mechanisms for peace and reconciliation.

The Bougainville conflict (1988–1998) stands as perhaps the most dramatic example of PNG's reliance on militarized solutions to address crises. Initially treated as a law-and-order problem, the conflict escalated into a full-scale civil war. Prime Minister Julius Chan's controversial 1997 attempt to hire Sandline International mercenaries reflected the desperation of the state to impose a military solution. The move backfired, sparking a mutiny within the Papua New Guinea Defence Force, mass protests, and ultimately the collapse of Chan's government (Dennin, 1997; Dorney, 2000). The eventual resolution came not through force but through political negotiation, with Prime Minister Bill Skate's government offering Bougainville the prospect of a referendum on independence as part of the peace settlement (Woodbury, 2015). The Bougainville experience highlighted the limits and dangers of militarized crisis management. It also revealed the fragility of PNG's state legitimacy when leaders prioritized coercion over dialogue, reconciliation, and institution-building.

Another emblematic crisis-driven response was the reintroduction of the death penalty. In 1991, the Namaliu Government reinstated capital punishment for willful murder through amendments to the Criminal Code (Papua New Guinea, Criminal Code (Amendment) Act 1991). More than two decades later, in 2013, the O'Neill Government expanded its application to cover sorcery-related killings, aggravated rape, and violent armed robbery (Papua New Guinea, Criminal Code (Amendment) Act 2013). These reforms were framed as strong deterrent measures in response to rising public concern about violent crime. Yet, critics argued that such legislation was largely symbolic, as PNG lacked the institutional and technical capacity to implement executions (Ferea, 1995; Sali, 2015). The failure to enforce the law underscored its performative nature, intended more to appease public opinion than to strengthen justice institutions.

Importantly, PNG's crime policies during this period were highly selective, prioritizing visible forms of disorder such as street crime, tribal violence, and urban unrest, often linked to unemployed youth (Harris, 1988). In contrast, white-collar and transnational crimes, typically committed by political and business elites, received far less attention despite their profound economic and social impacts (Dinnen, 1992; Pacific Island Report, 2012).

This imbalance reflected both political expediency and the state's reluctance to confront entrenched corruption. Watchdog bodies such as the Ombudsman Commission were systematically undermined (Clifford et al., 1984), limiting their capacity to hold elites accountable. Initiatives such as Task Force Sweep and the proposed Independent Commission Against Corruption (ICAC) signaled official recognition of corruption but were eventually dismantled through political interference once investigations implicated senior figures (Colvin, 2015). As Sir Mekere Morauta observed, corruption in PNG is both systematic and systemic, permeating governance at every level (Yuangua, 2001).

Taken together, these patterns demonstrate how PNG's law and order policies between 1986 and 2016 were reactive, selective, and crisis-driven. States of emergency, police deployments, militarized interventions, and harsh legal measures temporarily quelled disorder but failed to address structural causes of crime and instability. The neglect of systemic corruption, combined with an overemphasis on street-level crime, contributed to cycles of lawlessness, weakened governance, and declining public trust in state institutions. Unless PNG shifts towards proactive, balanced, and institutionally grounded crime-control strategies, crime will remain not only a symptom but also a driver of broader political and social instability.

5.4 State Struggles to Deal with Law-and-Order: 2016–2025

From 2016 to 2025, the Papua New Guinea government faced ongoing difficulties in managing law and order. Tribal conflicts, election-related violence, and corruption repeatedly exposed the limitations of state institutions. Law enforcement agencies often lacked the resources, training, and personnel to control crime effectively, leaving both rural and urban communities vulnerable (Post-Courier, 2017). Weak governance structures, limited coordination between national and provincial authorities, and underfunded justice systems meant that the state could rarely provide timely responses to violence. As a result, communities often turned to traditional leaders or vigilante methods, undermining the authority of formal government institutions.

Election-related violence highlighted the state's inability to maintain security during politically sensitive periods. During the 2017 and 2022 elections, killings, property destruction, and attacks on polling officials were widely reported (The Guardian, 2017; ABC News, 2022). Despite warnings from election observers and civil society organizations, the government struggled to prevent intimidation, deploy sufficient security, and enforce the law fairly (National Research Institute, 2022). The recurrent involvement of young unemployed people in electoral clashes also demonstrated the lack of effective youth engagement, employment programs, and civic education. These failures allowed violence to escalate, eroding public trust in democratic institutions.

Ethnic and tribal clashes in urban and peri-urban areas further illustrated government weaknesses. In 2023, serious fighting in Port Moresby caused deaths, injuries, and the closure of businesses (ABC News, 2023). Security forces were often slow to respond, and law enforcement's presence was insufficient to prevent escalation. The ready availability of weapons, combined with weak policing in high-risk neighborhoods, made these conflicts difficult to control. Schools, hospitals, and markets were disrupted, and the state struggled to provide protection and relief to displaced families, demonstrating gaps in emergency planning and crisis management.

The persistence of white-collar crime and corruption exposed institutional vulnerabilities at the highest levels of government. Misuse of public funds, bribery, and abuse of office continued to divert resources away from essential services (Transparency International, 2021; Post-Courier, 2019). Efforts to investigate and prosecute high-level corruption were often blocked or slowed by political interference. This limited accountability and signaled to citizens that law enforcement was uneven, favoring powerful elites over ordinary people. Weak monitoring systems, limited oversight, and under-resourced anti-corruption agencies contributed to an environment where corruption thrived and government credibility eroded.

Gender-based violence, including rape and sexual harassment, underscored additional state shortcomings. High rates of sexual violence against women and children persisted, particularly in remote areas, and many survivors could not access support services (UNICEF, 2024; UNFPA, 2023). Health centers and support facilities were often understaffed and poorly equipped (MSF, 2016), and in some cases, law enforcement itself was implicated in abuse, as in the 2025 reported case of rape in police custody (UN, 2025). The government's inability to enforce laws, provide survivor protection, and implement preventative programs showed deep structural weaknesses in addressing gender-based crime. Without stronger legislation, improved policing, and

comprehensive support services, these problems remain entrenched, highlighting the state's broader struggle to ensure safety and justice.

5. 5 The Criminal System at Work

The major components of the criminal justice system—Police, Courts, and Prisons—have struggled to address law-and-order issues in the country. The police function to protect citizens and their property by apprehending and arresting offenders, prosecuting them through the courts, and, where guilt is established, ensuring that convicted individuals are sentenced to prison. The convicted offenders are locked up in to serve the purposes of punishment, correction, segregation, and deterrence. However, since independence, in 1975, the criminal justice system has faced persistent administrative, logistic, and prosecution challenges, and these problems have continued through the 50 years of independence.

Table 1 below, for example, presents the prosecution cases recorded in 2023 by the Divisional Commands of the Royal Papua New Guinea Constabulary (RPNGC), which highlight typical prosecution challenges.

Table 1: PNGC Prosecution Cases Recorded for the year 2023 by Divisional Commands

Regions	2023 Cases	2022 Adjourned Cases	Committed	Grade 5	Conviction	Lost	Sinedie	Cases adjourned to 2024
NCD/Central	1,547	1,547	132	17	196	1,115	939	5,969
Northern	3,996	3,996	495	22	1,975	3,036	4	6,647
S outhern	352	352	84	8	241	432	2	1,486
H/lands East	1,927	1,927	101	45	882	1,320	42	2,065
H/lands West	337	337	23	1	144	305	0	903
NGI	1,446	1,446	115	11	616	935	55	2,776
Border	1,033	1,033	94	4	518	779	0	1,259
AROB	237	237	10	0	184	235	0	105
Total	**10,875**	**10,875**	**1,054**	**108**	**4,756**	**8,157**	**1,042**	**21,210**

Source: RPNGC, 2023

As observed above, a total of 10,875 cases were recorded across all divisional commands, with an equal number of cases carried over from 2022, highlighting systemic backlogs in case processing. Notably, the Northern region reported the highest volume with 3,996 new cases, followed by Highlands East and NCD/Central. This pattern points to population density and socio-economic pressures contributing to crime and legal disputes.

Despite the volume, only 1,054 cases were committed for trial, and convictions stood at 4,756. This suggests that while a proportion of the cases are successfully prosecuted, the majority face delays or fail to proceed due to capacity constraints, legal complexities, or resource limitations. In NCD/Central, for example, only 132 cases were committed, yet the number of cases adjourned to 2024 reached 5,969, stressing critical inefficiencies in judicial throughput and case management. Additionally, the high number of cases lost or categorized as "sinedie" (indefinitely suspended) across all regions reflects institutional weaknesses that need urgent reform.

Fifty years after gaining independence, the RPNGC's prosecution statistics serve as both a mirror and a call to action. They reflect the persistent structural, logistical, and human resource limitations affecting the justice system. Yet, they also highlight an opportunity to redefine and reform law and justice services in PNG.

6. WHAT ARE THE STRUCTURAL CAUSES OF THE LAW-AND-ORDER PROBLEMS?

As PNG celebrates fifty years of independence, it is timely to reflect not only on the nation's achievements but also on its enduring challenges. Among the most persistent is crime and law-and-order problems, which have long

been central to the country's struggle for stability and development. Crime in PNG is not merely an inefficiency issue for police, courts, or prisons to manage; rather, it reflects the combined effect of historical legacies, structural weaknesses, corruption, poverty, unemployment, and socio-economic hardship that have evolved across decades. Unless these root causes are properly addressed, crime will continue to constrain the nation's aspirations.

PNG's crime situation is shaped by its cultural diversity, colonial inheritance, and rapid modernization. With more than 800 languages spoken, it is one of the most culturally diverse nations in the world (Gordon, 2005; Turner, 1990). Governing such diversity with Western institutions and systems has always been a challenge. As Sali (1996:80) noted, the country resembles "a thousand tribes in one nation." In urban areas such as Port Moresby and Lae, where different ethnic groups with distinct norms coexist, competing values often create tensions that escalate into law-and-order problems.

The country's reliance on colonial-era governance systems has also played a role. Since 1975, PNG has operated under parliamentary democracy, bureaucratic administration, and judicial systems that were foreign to most of its population. Leaders and law-and-justice institutions have struggled to adapt these models to local realities, creating institutional weaknesses that criminals exploit (Dinnen, 1993a). At the same time, modernization has concentrated services and opportunities in urban centres, driving migration from rural areas. Many migrants, lacking education and formal skills, find themselves in informal settlements where unemployment and frustration fuel the rise of youth gangs or "raskols," who often resort to crime as a survival strategy (Harris, 1988).

Youth exclusion from education and employment further compounds the problem. The recent data from the Department of Higher Education, Research, Science, and Technology, (2024) (DHERST) that in 2023, there were 29,156 Grade 12 applicants, of whom 10,007 (about 34.3%) were selected for tertiary education. In 2024, applicants increased to 30,564, with 10,203 students selected (33.4%)—a slight decline in selection rate despite the growing number of applicants. The majority of school leavers are left without opportunities, and many drift into criminal activities. A study in Lae revealed that all 68 gangs surveyed consisted of individuals who had some schooling but turned to crime due to lack of jobs (Sali, 2014). This pattern highlights how structural failures in education and employment directly translate into youth crime.

Economic inequality and poverty also contribute to law-and-order problems. Strain theory helps explain why disadvantaged individuals, unable to achieve their goals legitimately, resort to crime. In Lae, gangs studied by Sali (2014) engaged in theft, robbery, and shoplifting largely to meet basic needs such as food. Earlier studies have also shown socio-economic pressures to be major drivers of property crime in the country (O'Collins, 1984; Uki, 2010; Sali, 2016). While these forms of crime are visible in everyday life, white-collar crime and corruption are equally, if not more, destructive. Former Public Service Minister Bart Philemon estimated that PGK 1 billion is lost annually through corruption (Pacific Island Report, 2012), while Prime Minister Peter O'Neill admitted that the country could no longer sustain such losses (ibid., 2012). The consequences are severe: corruption drains resources from health, education, and law enforcement, undermining development. Papua New Guinea's ranking of 145 out of 178 countries in the 2015 Transparency International Corruption Perceptions Index illustrates the magnitude of this issue (Transparency International, 2015).

Corruption in PNG is closely connected to the roles of the Legislature and the Executive, which need clearer separation and reform so that one branch does not interfere with the work of the other. Sali (2024), in his study of the 2022 National General Election violence, shows how weaknesses in the country's three branches of government are linked to the outbreak of election-related violence. He explains that corruption is not just the result of individual actions but is built into the overlap between the Legislature and the Executive. Under the District Development Authority Act (2014), especially Section 12, Members of Parliament are given direct control over large amounts of district funds and the power to decide development priorities. This gives MPs a dual role as both lawmakers and local administrators, which weakens the separation of powers and encourages political favoritism. According to Sali, this situation creates a belief that being elected to Parliament is the main pathway to wealth and resources for both individuals and communities. For many voters, supporting a candidate is seen as a way to gain direct access to state funds, rather than simply choosing a representative. This has made elections highly competitive, with candidates and supporters often resorting to threats, intimidation, and violence to win. The 2022 General Election clearly revealed these problems, as violence broke out across constituencies, showing how unclear governance roles and the use of money in politics continue to weaken democracy and fuel corruption, violence and instability contributing to the wide law-and-order issues in PNG.

At fifty years of independence, crime remains one of the greatest obstacles to national progress. The combination of cultural diversity, imported governance systems, rural-urban drift, youth exclusion, poverty, and corruption shows that crime is deeply embedded in the country's social fabric. Addressing these challenges requires more than reinforcing police and prisons; it calls for holistic strategies that deal with structural inequalities and institutional weaknesses. As PNG reflects on its journey since 1975, acknowledging the realities of crime is crucial if it is to chart a safer, more stable, and prosperous future.

7. FORGING A NEW APPROACH: LESSONS FROM THE PAST AND A PATH FORWARD

As PNG marks 50 years of independence, it is critical to reflect on the country's law-and-order experiences and chart a course for the next fifty (50) years. The nation has faced continued challenges of white-collar crime and corruption; transnational crimes; ethnic conflicts; property crimes; crimes against persons (murder, rape, assault and so on); protest and strikes; election-related violence; and gender-based crimes. These challenges have exposed weaknesses in governance, policing, and justice systems, and leadership. To build a safer and more prosperous future, PNG needs a forward-looking, proactive, and technology-driven framework that addresses both the symptoms and root causes of crime. In the next 50 years, as we move on as nation, let us be guided by a framework in address the law-and-order.

Figure 1 below presents a 50-year strategic agenda that provides a forward-looking pathway for PNG as it enters the next half century of nationhood. At the core is the nation itself, supported by integrity in leadership at the top, with stronger governance, zero-tolerance for corruption, and the upholding of the rule of law and separation of powers as essential guiding principles. Enforcing an effective criminal justice system and eliminating illegal firearms remain critical priorities. By aligning education with employment, driving technological advancement, and revitalizing the economy, this strategy aims to build a safer, more prosperous, and resilient PNG for future generations.

Figure 1. PNG Law-and-Order: 50-year Strategic Agenda – 2025-2075

Source: Garry Sali, 2025

7.1 People of Papua New Guinea

The country of PNG is not just land or resources, but a nation of nearly 12 million people (PNG 2011 Census). This strategic agenda places the people of PNG at the core of development, recognizing that human development is central to nationhood. When our forefathers framed the Constitution, they placed people first, affirming that the integral development of our citizens is more important than anything else. That is why the model in Figure 1 above positions the people of PNG at the heart of all efforts to create a peaceful society.

For peace, law, and order to be sustained, the instruments of the state must function effectively. The eight elements presented above (integrity in leadership, rule of law, separation of powers, strong governance, zero tolerance for corruption, an effective criminal justice system, elimination of illegal firearms, education aligned with employment, and technological advancement) all point back to PNG and its people as the foundation of this vision.

7.2 Uphold the rule of law and the Spirit of the Separation of the Powers

Every citizen and visitor in PNG, regardless of social, economic, or political standing, must respect and abide by the nation's laws. The law applies equally to all, and no individual stands above or beneath it. Political leaders, in particular, must exercise restraint and avoid altering laws for selfish or harmful purposes. As PNG looks ahead to the next fifty years, sustained progress in peace, law, and order will depend on the consistent upholding of the rule of law by everyone. Building a peaceful society is the shared aspiration of all nations, but it is never achieved effortlessly, it requires commitment, discipline, and hard work. PNG must therefore strive with determination to secure and preserve the peace it desires.

A clear separation of powers between the legislature and the executive is vital to prevent abuse of office and overlapping authority. Members of Parliament must have clearly defined responsibilities that separate lawmaking and policymaking from administrative execution, thereby reducing opportunities for political interference in daily governance. Strengthening the capacity of the public service is equally important to ensure that citizens receive essential services efficiently and fairly, particularly in remote and underserved areas where government presence is limited (Post-Courier, 2019). The legislature should focus on oversight, monitoring policy implementation, and scrutinizing the use of development funds to guarantee that projects achieve their intended outcomes.

Looking ahead to the next 50 years, PNG must urgently reconsider how development funds are managed and distributed. Under the current arrangement, Members of Parliament for open electorates automatically serve as chairpersons of District Development Authority (DDA) Boards, as provided for in Section 12 of the District Development Authority Act 2014. These boards hold significant authority in deciding how development funds are allocated to projects within the districts. However, when an open electorate MP assumes the role of chair, he or she performs a dual function, serving both as a legislator and as an executive decision-maker. This dual role conflicts with the principle of separation of powers enshrined in the PNG Constitution. To move confidently into the next half-century, PNG must resolve this inconsistency and establish clearer boundaries that safeguard accountability, transparency, and good governance in the use of public funds.

7.3 Enforce an Effective Criminal Justice System

A strong criminal justice system is central to achieving law-and-order. PNG must ensure that its police, courts, and correctional facilities have sufficient and well-trained manpower to respond effectively to crime (Post-Courier, 2017). Modernized prisons are necessary to provide rehabilitation, education, and vocational training, ensuring that offenders can reintegrate into society as productive citizens. Effective policing requires a shift from reactive enforcement to proactive, community-based approaches, including rapid response units in high-risk areas. Strong legislative oversight, including parliamentary committees to monitor criminal justice policies, can ensure that resources are used efficiently and that institutions remain accountable. Lessons from past decades show that without sufficient resources, trained personnel, and accountability mechanisms, law enforcement efforts are often temporary and ineffective.

Inefficiencies within PNG's criminal justice system were identified as early as independence in 1975 (1976), and over the past fifty years, many of these same challenges—such as inadequate policing, delays in court processes, outdated correctional systems, and limited resources—have persisted, repeatedly surfacing in policy debates and public forums. As the nation marks its 50th year of independence, the pressing question arises: will these problems still exist in 2075? It is no longer sufficient to merely acknowledge them; PNG must now take bold steps to modernize its criminal justice system by addressing structural, administrative, and operational weaknesses, including strengthening institutional capacity, investing in manpower and technology, combating corruption, and ensuring justice is timely and accessible for all citizens. The next fifty years cannot repeat the failures of the past; this is a time for decisive action, guided by innovation, accountability, and long-term vision, so that a peaceful and lawful society becomes a reality rather than an ongoing aspiration.

7.4 Strengthen Good Governance and Promote Zero-Tolerance Corruption

The international community widely recognizes PNG as one of the most corrupt nations globally. According to Transparency International's 2023 Corruption Perceptions Index (CPI), PNG scored 29 out of 100, indicating a high perceived level of public sector corruption (Transparency International, 2023). This persistent issue is not only widespread but also deeply embedded within the country's institutions. Former Prime Minister Mekere Morauta aptly described corruption in PNG as "endemic, systemic and systematic," highlighting its pervasive nature across all levels of governance (Post-Courier, 2020). The systemic and systematic nature of corruption in PNG suggests that it is not merely a series of isolated incidents but a structural problem that affects the functioning of public institutions and governance.

The Deputy Opposition Leader of PNG, Hon. Donald James, has urged the government to show genuine commitment to reform, while the Prime Minister, Hon. James Marape, emphasized that PNG needs a "nation reset" to tackle corruption and promote good governance (Post-Courier, 2025). Yet, these calls risk being perceived as mere political rhetoric, as the country's anti-corruption institutions often appear powerless, like "big tigers without teeth." Strengthening independent bodies such as the Independent Commission Against Corruption (ICAC) is critical to ensure investigations and prosecutions proceed without political interference (DevPolicy, 2020). Transparency in public spending must be enforced through digital monitoring systems, while parliamentary oversight should mandate regular reporting and auditing of government projects. Independent audits and strict sanctions for non-compliance are essential to reinforce accountability. The past fifty years demonstrate that unchecked corruption diverts resources from essential public services, leaves communities underserved, and erodes public confidence. By putting in place transparency, accountability, and strong institutional oversight, PNG can create a foundation for effective law-and-order enforcement and good governance (DevPolicy, 2020; Post-Courier, 2025).

7.5 Elimination of Guns and Ammunition

The spread of illegal firearms has intensified violence in PNG, particularly within tribal warfare, urban ethnic conflicts, and the rascal gang context. Addressing this issue requires a detailed strategy that includes strengthening border security and deploying modern tracking systems to curb the influx of illicit weapons. Regular audits of police and defense armories are essential to ensure accountability, while strict licensing and registration laws can serve as deterrents against unauthorized ownership. Intelligence-driven operations that dismantle arms smuggling networks, combined with the prosecution of corrupt officials who enable the illegal gun trade, are equally critical. At the community level, reporting mechanisms and firearm buy-back programs provide citizens with opportunities to actively support disarmament efforts. Evidence from the past decade highlights that the presence of firearms increases the escalation of violence and conflicts, making it difficult to maintain peace and security at both local and national levels

Guns and ammunition must be eliminated from civilians. Retired Major General Jerry Singirok's detailed 2005 gun control report, comprising 244 recommendations, advocated primarily for a complete ban on civilian ownership of firearms, asserting that "there is no need for Papua New Guinean citizens to own a gun," and proposing that only security services should be permitted to carry weapons (Singirok, 2025; RNZ, 2022). As we

march on after 50 years of independence, the elimination of guns and ammunition is a strategic move, and it must be a priority for the government because guns are used to kill people and burn down state and private properties.

7.6 PNG Education System and Employment

The education system in Papua New Guinea—spanning primary, secondary, and tertiary levels—must undertake intentional reforms aimed at transforming the mindset of students, parents, and the broader public. Historically, education in PNG has been viewed primarily as a pathway to formal employment, a perception that limits the role of education in fostering self-reliance and innovation (Papuaniugini.org, 2023). A broader perspective is needed—one that emphasizes the acquisition of knowledge, skills, and attitudes to prepare individuals for diverse life opportunities. Embedding an entrepreneurial mindset across all levels of education is therefore essential. Higher education institutions such as IBS University have begun fostering entrepreneurship, with promising outcomes in venture initiation and institutional reputation, but significant challenges remain due to resource constraints, gender inequities, and inadequate post-graduation support (Dadam, 2024; The National, 2024). Similarly, initiatives such as the Teen Entrepreneur program, supported by UNICEF and Education Partnerships, have been piloted to strengthen entrepreneurial teaching and learning at the primary level (Education Partnerships, 2023).

At the policy level, the PNG government is reorienting education to emphasize job creation rather than job-seeking, with reforms that integrate business ethics, technical and vocational education, and entrepreneurial competencies into the national curriculum (Edu PNG Facts, 2021). Collectively, these initiatives underscore the importance of reconceptualizing education as more than a preparation for wage employment. Instead, it should be understood as a vehicle for developing entrepreneurial spirit, self-reliance, and innovation, enabling Papua New Guineans to apply their skills not only in formal employment but also in creating sustainable livelihoods and contributing to national development.

7.7 Drive Technological Advancement

Technology offers transformative potential for law-and-order in PNG. Implementing secure digital IDs and e-governance systems can enhance service delivery, while blockchain technology ensures transparent government transactions and reduces corruption. Smart surveillance systems, AI-driven crime analytics, and cybersecurity frameworks improve policing efficiency and protect citizens from digital and physical threats. Online anti-corruption reporting platforms enable safe, anonymous citizen engagement, while biometric voter verification reduces election fraud. By embracing technology strategically, PNG can create a modern, proactive, and responsive law-and-order system, building on lessons learned from decades of reactive and crisis-driven approaches (UNICEF, 2024; UNFPA, 2023).

7.8 Create, Revitalize, and Stimulate the PNG Economy

Law-and-order concerns in PNG are not stand-alone issues but are deeply intertwined with the broader economy. These challenges stem largely from weaknesses in governance and the economic system, and in turn, they significantly undermine economic performance. Looking ahead, PNG's future depends on transforming its economy into a K200 billion powerhouse by 2030 and beyond, a target articulated by Prime Minister James Marape (PNG Business News, 2025). Central to this vision is the empowerment of small and medium enterprises (SMEs), described as the "heartbeat of PNG's economic future," supported through credit-guarantee schemes, export-licensing reforms, state equity participation in import-replacement sectors, zero-tax thresholds, and GST relief on essential goods, all designed to stimulate inclusive, resilient growth (PNG Business News, 2025a). Complementing this, the launch of the Special Economic Zones (SEZ) Foundation Policy 2025–2032 signals a strategic pivot toward industrialisation, rural development, and economic diversification including agriculture, fisheries, manufacturing, and tourism; moving beyond past dependence on extractive sectors and projecting over a million new jobs and significant foreign investment (PNG Business News, 2025b).

7.9 Leadership with Integrity

Ethical leadership forms the cornerstone of national progress, and PNG is no exception. Leadership that embodies integrity, transparency, accountability, fairness, and decisiveness is vital for sustainable development. Importantly, this responsibility extends beyond the political sphere to all sectors of society, including government institutions, private enterprises, and community organizations. Even at the personal level, the demonstration of sound leadership principles contributes to building a just and progressive society.

Tackling law-and-order problems is, first and foremost, a political matter that demands strong will from leaders. Technical fixes alone are not enough if the political courage to act is missing. Leaders must be willing to make tough choices, even when those choices are unpopular. One example is dealing with illegal firearms, which requires bold steps such as stopping the easy issuance of gun licenses to citizens. Making these difficult but necessary calls reflects the type of firm leadership needed to restore order and build safer communities in the country.

8. CONCLUDING REMARKS

As PNG marks its 50th Golden Jubilee, it is timely to pause, reflect, and critically assess our journey since 16th September 1975. The past five decades have been marked by challenges and achievements that collectively define our national identity. Looking ahead, it is equally important to envision what our country might become on 16th September 2075. Although many of us may not be present to witness the second Golden Jubilee, the character of that future PNG will depend on the choices, values, and commitment of today's generation, just as the progress of the last fifty years was shaped by those who came before us. Our responsibility, therefore, is not only to reflect on the road already traveled but also to ensure that we pass the torch of nationhood with purpose and vision to the generations that will follow

This paper has discussed the trajectory of PNG's law-and-order experience since independence. It reflects on the extent to which the nation has managed its socio-economic and political structures over the past fifty years to promote peace, stability, and social cohesion. The discussion highlights how law-and-order has been integral to ensuring not only security but also the stability of livelihoods and the quality of life for Papua New Guineans. In doing so, the paper also considers how lessons from the past can inform new approaches that will shape the country's law-and-order landscape as it enters the next fifty years of independence.

PNG's law-and-order trajectory over the next 50 years requires drawing lessons from past challenges while committing to systemic reforms. Strengthening the criminal justice system, enhancing governance, clarifying institutional roles, addressing education-to-employment gaps, regulating firearms, and leveraging technology form a holistic framework for progress. Through proactive measures, citizen participation, and institutional transparency, PNG can be a safer and more equitable society capable of sustaining peace and order into the future.

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From Knowledge to Action: Enhancing Decision-Making through Science -Policy Integration for Papua New Guinea

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Abstract: This paper, titled *"From Knowledge to Action: Enhancing Decision-Making through Science-Policy Integration,"* explores the relationship between science and policy in Papua New Guinea. The study emphasizes that, given the country's extraordinary biological and cultural diversity, effective decision-making must rely on both scientific evidence and local knowledge systems. Currently, weak links between Papua New Guinea's unique assets and science policy hinder progress affecting many of country's societal, environmental and economic problems. This disconnect limits the nation's ability to leverage knowledge for innovation, entrepreneurship, environmental sustainability, and socio-economic development. The study advocates for a science-policy interface that integrates indigenous knowledge with modern scientific research, viewing this integration as essential for fostering a knowledge-based economy and society—key prerequisites for sustainable growth. The paper concludes that increasing interaction among policymakers, scientists, knowledge producers, and stakeholders is crucial to bridge the gap between science, policy, and action, ensuring decisions are informed by relevant, robust evidence. To improve policies related to environmental management, health, agriculture, and climate change, Papua New Guinea needs to strengthen data collection systems, boost research funding, and foster partnerships among government, academia, and civil society. Future efforts should focus on building local scientific capacity and translating research findings into actionable policies that benefit both communities and the environment.

Keywords: Knowledge, action, Papua New Guinea, Science-Policy Integration, Decision-Making.

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1. INTRODUCTION

1.1 Background and Context

In the contemporary era of globalization and rapid change, the transition from knowledge to action has become a critical driver of national development. For Papua New Guinea (PNG), a country endowed with extraordinary biological and cultural diversity (Groube,1989) effective decision-making must be grounded in both scientific evidence and traditional knowledge systems. The complex land tenure systems, customary practices, and indigenous stewardship of resources in PNG underscore the need for a science-policy interface that respects and integrates indigenous knowledge alongside modern scientific research. This approach is central to fostering a knowledge-based economy and society—preconditions for sustainable growth and development, as emphasized by Grueber et al. (2009). Despite PNG's wealth of ecological and cultural capital, its persistent challenge lies in the weak linkage between these unique assets and limited capacity in manufacturing, industry and market. This disconnect hampers the nation's ability to harness knowledge for innovation, entrepreneurship, and socio-economic advancement. Hor (2010) argues that investments in research and growth of national development is evidently proportional, highlighting the urgency of strengthening research and science-policy mechanisms. Greater interaction between policymakers, scientific communities, knowledge producers, and consumers is vital to bridge this gap and ensure that decisions are informed by robust, context-relevant evidence. Integrating science and policy in PNG is more than a technical requirement; it is a pathway to inclusive, rights-based, and sustainable development. By aligning indigenous and scientific knowledge through effective policy frameworks, PNG can enhance service delivery, support

technological innovation, and safeguard its ecosystem for future generations. For example, study by Kanowski et al (2008), Mulung (2012) observed small-holder tree-farmer adoption behaviour and attitude to uptake and integration of scientific and traditional agroforestry knowledge system into opportunities for commercial tree farming are possitive when benefit to the decision-maker was evidently clear and policy support for such intervention was present. Elsewhere similar observation were documented by Pannell et al (Pannell et al, 2006), and Rogers (Rogers, 1995).

1.2 Challenges in Translating Scientific Knowledge into Policy in PNG

Papua New Guinea faces significant hurdles in bridging scientific research with policymaking processes. One major challenge is the limited capacity within government institutions to interpret and apply complex scientific data, often due to resource constraints and a shortage of skilled personnel (Koczberski et al., 2014). Additionally, there is a persistent gap between scientific research outputs and policy agendas, partly because research findings are not always accessible or communicated effectively to decision-makers (Tao et al., 2019). Furthermore, there is often a disconnect between scientists and policymakers due to differing terminologies, priorities, and timelines (Lavis et al., 2003). Scientific findings may be too technical or lack clarity for policymakers to understand and utilize effectively. Political considerations and socio-cultural factors also influence policy decisions, sometimes leading to the marginalization of scientific evidence—especially in areas like resource extraction, land use, and climate adaptation (Friedman et al.; 2017; Cash et al.,2003). Furthermore, PNG's diverse cultural landscape and traditional knowledge systems can complicate the integration of scientific insights into policies that are socially acceptable and practically implementable. Additionally, uncertainties inherent in scientific research can undermine confidence among policymakers, delaying or complicating decision-making processes (Pielke, 2007). Finally, inadequate communication channels and limited engagement between scientists and policymakers further obstruct the integration of scientific knowledge into policy frameworks.

1.3 Significance of Science-Policy Integration for PNG's resilient and sustainable development

For PNG, where natural resources underpin economic growth and ecological health is vital for livelihoods, integrating scientific knowledge into policy is crucial for achieving sustainable development. Effective science-policy linkages can inform policies on climate resilience, biodiversity conservation, and sustainable resource management, which are critical for PNG's future (Tao et al., 2019). Enhancing these linkages ensures that development strategies are evidence-based, culturally sensitive, and environmentally sustainable. Given PNG's vulnerability to climate change impacts such as rising sea levels, extreme weather events, and ecological degradation, science-informed policies are necessary to develop adaptive strategies that protect both ecosystems and communities. Strengthening science-policy interfaces can thus promote resilient, inclusive, and sustainable growth aligned with the nation's development goals.

1.4 Objectives and Scope of the study

This study explores how science-policy integration can enhance decision-making in PNG, emphasizing the importance of building a knowledge-driven society that is responsive to its unique cultural and environmental contexts. The paper examines current gaps, opportunities for improvement, and strategies for effective integration of science-policy in Papua New Guinea. Effective science-policy integration is crucial for PNG's future, requiring tailored approaches that bridge gaps and policy needs.

2. DEFINITIONS AND THEORETICAL PERSPECTIVES

2.1 Definitions

Evidence-informed decision-making has the potential to improve the effectiveness, efficiency and equity of the decisions that are made, while also enhancing accountability and transparency. Yet integration of science and evidence into effective agrifood systems decision-making processes remains a significant challenge (Nature, 2022). A narrow view of what counts as evidence favours specific expertise over others, and a wide range of evidence remains undocumented, unpublished and overlooked, leading to bias. This limits a nuanced understanding of different agrifood systems (Global Alliance for the Future of Food, 2021). There also exists a noticeable disparity between the volume of knowledge available and the capacity to make sense of it. Scientific findings may be limited by complexity, insufficient data, differences in values, uncertainties, competing views and contrasting results, and can be contested. Co-creating and integrating knowledge from different knowledge systems and across various sectors, scales and social actors can be fraught and politicized because knowledge is not neutral. The determination of what holds value and is valid is influenced by lived experiences, spiritual beliefs and cultural norms, in addition to science.

Delivering the best available evidence to policymakers in a timely and a useful format is not straightforward. Policy implementation can sometimes be rapid, yet even when unequivocal knowledge has been garnered over a long period, policy development and application can be very slow despite the acknowledged urgency of a problem (for example with climate change, there is a gap between scientific knowledge and policy uptake, and evidence alone has not been sufficient to influence political decisions). While policymakers do employ the evidence they perceive as most helpful to set priorities and design or inform policies (Masaki et al., 2017), there is often a disconnect in terms of how scientists conceive evidence as relevant for policymaking versus what policymakers consider relevant for decision-making (Avey and & Desch, 2014). The significant differences in goals and incentives between scientific research and policymaking are often overlooked by both, posing challenges in their relationship, especially when dealing with contentious issues that can undermine trust among stakeholders. Policymakers may not inform scientists and other knowledge holders about their needs while scientists and other knowledge holders may not actively engage in the policymaking process. Additionally, many obstacles may compromise their participation.

2.2 Theoretical Perspectives: Models of Science-Policy Interaction

The interaction between science and policy is critical for developing effective governance and addressing complex societal challenges. Various models of science-policy interaction, including linear, interactive, co-production, and knowledge translation models, offer different frameworks for understanding how research can inform decision-making.

The existing models of science-policy interaction consists of linear model, interactive Model, co-production model and ***k*nowledge *t*ranslation *m*odel.**

Linear Model. This traditional model posits a one-way flow of information where scientific research is conducted independently and later disseminated to policymakers. While straightforward, this approach often fails to account for the dynamic and multifaceted nature of policymaking, leading to the underutilization of research findings (Weiss, 1979).

Interactive Model. In contrast, the interactive model promotes a two-way exchange between researchers and policymakers. This model emphasizes the importance of dialogue, allowing for a better understanding of policy needs and context, thus enhancing the relevance of research outputs (Cash et al., 2003).

Co-Production Model. Co-production goes a step further by involving stakeholders in the research process itself. Researchers and policymakers collaboratively define research questions, methodologies, and implementation strategies. This model fosters mutual learning and ensures that the research is both relevant and applicable, as it integrates diverse perspectives (Brouwer et al., 2018).

Knowledge Translation Model. This model focuses on the systematic approach to bridging the gap between knowledge creation and its application in policy. Knowledge translation encompasses strategies that

make research findings accessible and actionable for decision-makers, considering the specific contexts in which policies are implemented (Graham et al., 2006).

3. IMPORTANCE OF INTEGRATION FOR DECISION-MAKING

3.1 Integration of Scientific Research into Policymaking

The integration of scientific research into policymaking is essential for promoting evidence-based policies, adaptive management, and resilience-building.

Evidence-Based Policies: Integrating research ensures that policy decisions are grounded in the best available evidence, which enhances their effectiveness and accountability (Nutley et al., 2007). Evidence-based policies are more likely to address the actual needs of communities and lead to favorable outcomes.

Adaptive Management: The integration of scientific knowledge allows for adaptive management practices that can respond to changing conditions and uncertainties (Holling, 1978). This flexibility is crucial in fields such as environmental management, where ecosystems are dynamic and subject to various stressors.

Resilience-Building: Effective integration fosters resilience by equipping communities and institutions to withstand and recover from shocks and stresses. Evidence-informed decision-making can identify vulnerabilities and guide strategies that enhance adaptive capacity (Folke et al., 2002).

3.2 Barriers to Integration

Despite the benefits of integrating science and policy, several barriers hinder this process, including: Political challenges, cultural challenges, institutional challenges and knowledge-related challenges.

Political challenges: Political interests and agendas can obstruct the incorporation of research into policy. Decision-makers may prioritize short-term goals or be swayed by lobbying efforts, leading to the marginalization of evidence-based approaches (Pielke, 2007).

Cultural challenges: Divergent organizational cultures between research institutions and policy bodies can create misunderstandings and misalignments. A lack of shared values and priorities can impede effective collaboration and knowledge sharing (Gulbrandsen, 2008).

Institutional challenges: Rigid institutional frameworks and bureaucratic processes can limit the capacity of organizations to adopt evidence-based practices. Insufficient resources and support can further exacerbate these limitations (Elmore, 2000).

Knowledge-related challenges: Gaps in knowledge, limited awareness of existing research, and the complexity of certain issues can hinder effective application of research findings in policy contexts (Rosenberg, 1992).

In summary, the interaction between science and policy is essential for developing effective, evidence-based governance. By utilizing models such as co-production and knowledge translation, stakeholders can enhance the relevance and applicability of research findings. However, addressing the barriers posed by political, cultural, institutional, and knowledge-related challenges is crucial for fostering meaningful integration that ultimately leads to improved decision-making outcomes.

4. CURRENT STATE OF SCIENCE AND POLICY IN PAPUA NEW GUINEA

4.1 Overview of Scientific Research and Data Availability

In recent years, PNG has made strides in scientific research, although it remains constrained by limited funding, infrastructure, and human resources. The country's unique ecosystems, including rainforests and coral reefs, require comprehensive data to inform conservation and management efforts. Research institutions, universities, industry and various civil society organisations engage actively in scientific inquiry, but the overall output is often hampered by the lack of consistent funding and resources (STCS, 2016). Governments investment in scientific

research stands at 0.03% of Gross Domestic Product (STCS 2016). Of these personnel accounted for 77%, and other capital accounted for 23%. In terms of research, basic research accounted for 55 %, 28% on applied research, and 16% 16 %. Break-up this by sector are biological sciences 38%, agriculture sciences 21% and other areas of sciences 39%. By contrast, other OECD countries average about 2.27% of National Gross Domestic Product.

4.2 Key Sectors

Summary performance by the different sectors in Papua New Guinea are.

4.2.1 Environmental Management

Environmental management in PNG is critical due to its rich biodiversity and the increasing pressures of deforestation, mining, and industrial development. Various research initiatives have focused on biodiversity assessments and conservation strategies. For instance, the establishment of protected areas and the promotion of sustainable practices are increasingly informed by scientific studies. However, the availability of data on species distribution and ecosystem health is often fragmented and outdated (Govan et al., 2011).

In recent years, efforts have been made to improve data collection through partnerships with international organizations and NGOs. Projects like the Papua New Guinea Conservation and Environment Protection Authority's (CEPA) initiatives emphasize the need for comprehensive environmental assessments (CEPA, 2018). Yet, despite these advancements, the capacity for effective data management and dissemination remains a significant hurdle. Local communities, who are often the stewards of these environments, frequently lack access to vital information that could guide sustainable practices (Govan et al., 2011).

4.2.2 Health

The health sector in PNG faces numerous challenges, including high rates of communicable diseases, maternal and child health issues, and emerging threats from non-communicable diseases. Scientific research in public health has been crucial in understanding these challenges and informing policy responses. The National Department of Health (NDoH) collaborates with international partners to conduct epidemiological studies and health surveys, yet data availability is still inconsistent (PNG NDoH, 2020).

One of the notable advancements in health research has been the focus on malaria, tuberculosis, and HIV/AIDS. The PNG Institute of Medical Research (PNGIMR) plays a vital role in this regard, conducting research that informs national health policies and interventions (PNGIMR, 2019). However, data collection methods can be inadequate, particularly in rural areas where access to healthcare is often limited. Strengthening data collection and surveillance systems, particularly in remote communities, is essential for effective health policy formulation.

4.2.3 Agriculture

Agriculture is a cornerstone of PNG's economy, supporting the livelihoods of much of the population. Scientific research in agriculture has focused on improving crop yields, pest control, and sustainable farming practices. Institutions like the National Agricultural Research Institute (NARI) have been pivotal in conducting research that addresses food security and agricultural sustainability (NARI, 2021). The study by Allen, Bourke, and McGregor (2009) discusses the critical policy challenges affecting food security in Papua New Guinea. It explores how issues such as agricultural productivity, land management, climate variability, and socio-economic factors influence the country's ability to ensure reliable access to sufficient, safe, and nutritious food for its population. The study emphasizes the need for integrated science policy approaches that incorporate local knowledge and sustainable practices to improve food security outcomes in PNG. Despite the importance of agriculture, challenges remain in data availability and accessibility. Many farmers lack access to current agricultural practices and research findings, which can lead to inefficient farming methods. Moreover, climate change poses a significant threat to agricultural productivity, necessitating the integration of climate-resilient practices into farming. Efforts to enhance

agricultural research have been bolstered by partnerships with international organizations, but the need for localized research tailored to PNG's diverse ecological conditions remains critical (NARI, 2021).

4.2.4 Climate Change

As one of the countries most vulnerable to climate change, PNG faces severe challenges related to rising sea levels, extreme weather events, and changes in rainfall patterns. Scientific research on climate change impacts and adaptation strategies is essential for informing national policy and community-level responses. The National Climate Change Policy outlines the government's commitment to addressing climate change, yet implementation remains a challenge (Government of Papua New Guinea, 2015).

Research institutions and NGOs have been active in climate-related studies, focusing on vulnerability assessments and adaptation strategies. However, climate data is often insufficient, and there is a pressing need for comprehensive climate modeling and projections specific to PNG's diverse environments. Building local capacity for climate research is crucial, as is fostering collaboration between scientists, policymakers, and local communities (Mastrorillo et al., 2016).

4.2.5 Science and Technology Council

The Council of Science and Technology serves as the highest authority responsible for governance in matters related to science, technology, and innovation in Papua New Guinea, as outlined in the PNG Science and Technology Council Act of 1992 (Office of Legislative Council, PNG, 2022). Recently government approved National Research Agenda for prompt implementation, focusing on seven strategic areas aimed at fostering growth (PNGSTCS, 2016).

The first area, Human Capital, Health, Youth, and Gender, seeks to enhance the overall well-being of the population by investing in research focused on human capital development, strengthening healthcare systems, empowering youth, and addressing gender inequalities. Research in this domain promotes health, education, and gender equity.

The second focus area, Wealth Creation, emphasizes research and innovation in agriculture, industry, and entrepreneurship to stimulate economic growth, create jobs, and alleviate poverty.

The third area, Institutional Development and Service Delivery, underscores the need for research into effective institutions and efficient service delivery, which are vital for good governance and citizen welfare. This research aims to improve governance structures and enhance the quality and accessibility of public services.

The fourth area, Security and International Development, directs research efforts towards ensuring national safety and stability while promoting productive international collaborations for mutual advancement.

The fifth area, Environment and Climate, addresses the pressing environmental challenges and climate change, focusing on conservation, sustainable resource management, and building climate resilience. This includes examining environmental health and its effects on communities.

The sixth focus area, Spiritual Cultural Society, recognizes the rich cultural diversity of the country and highlights the importance of researching the preservation and promotion of indigenous cultures, languages, and traditions. This research aims to empower communities to protect their heritage and identities.

The final area, Planning Integration and Control, emphasizes the importance of policy formulation, coordination, and monitoring to ensure the efficient implementation of national strategies.

These seven focus areas create a comprehensive framework for research and development in Papua New Guinea, addressing critical social, economic, and environmental issues while respecting the nation's cultural heritage and promoting effective governance and planning. Collaborative efforts among researchers, policymakers, and stakeholders within these themes will propel the nation forward and enhance the quality of life for all citizens.

5. CHALLENGES IN KNOWLEDGE-TO-ACTION FOR PAPUA NEW GUINEA

5.1 Structural and Institutional Challenges

Papua New Guinea (PNG) faces significant structural hurdles, including limited research capacity and inadequate infrastructure PNG Science and Technology Council Secretariat (2016). Many local institutions lack the resources, skilled personnel, and facilities necessary to conduct and disseminate research effectively (PNG Science Technology Council Secretariat, 2016). This hampers the generation of actionable knowledge tailored to local contexts. Additionally, there is notable fragmentation among government agencies, NGOs, and other stakeholders involved in development and policy implementation World Bank (2018). This disjointed landscape results in duplicated efforts, poor coordination, and a lack of unified strategies, all of which impede the translation of evidence into effective action.

5.2 Cultural and Societal Barriers

PNG's rich indigenous cultures and traditional knowledge systems often operate parallel to Western scientific approaches. While indigenous knowledge is invaluable for local understanding and sustainable practices, there can be conflicts or misconceptions about its validity within mainstream policy frameworks Asian Development Bank (ADB) (2021). Communication gaps also exist, stemming from language diversity, literacy levels, and differing worldviews Hunt, C. (2013). These barriers make it difficult for scientific findings and policy recommendations to be effectively communicated and adopted by local communities and decision-makers.

5.3 Policy and Political Challenges

Political stability and consistent policy focus are often lacking in PNG, Allen M., Bourke, R.M, & McGregor (2009). The country's political landscape frequently prioritizes short-term gains over long-term development, driven by electoral cycles and shifting government priorities, World Bank (2018). This environment results in a lack of sustained commitment to evidence-based policies. Political instability and limited political will further undermine efforts to institutionalize research findings into actionable policies, leading to gaps between knowledge generation and practical implementation.

5.4 Knowledge Gap Issues

There is a persistent deficiency in quality, comprehensive, and context-specific data in PNG (PNGSTCS, 2016), Allen M., Bourke, R.M, & McGregor (2009). Many sectors lack reliable information that reflects local realities, which is crucial for designing effective interventions. Data collection can be hampered by logistical challenges, limited technical expertise, and resource constraints. Without relevant and high-quality data, policymakers and stakeholders struggle to make informed decisions, hindering the translation of research into tangible actions that address community needs and ecological realities.

This constellation of challenges—structural limitations, cultural considerations, political dynamics, and data gaps—creates a complex environment where turning knowledge into effective action remains a significant hurdle in PNG's development journey. Addressing these issues requires coordinated efforts across sectors, capacity-building, enhancing data systems, and integrating indigenous knowledge into policy frameworks

5.5 Opportunities and Strategies for Enhancing Science-Policy Integration

This section provides brief notes, selected references and key action are suggested as opportunities and strategies for enhancing science policy integration for Papua New Guinea.

5.5.1 Building Capacity and Infrastructure

Strengthening research institutions improves local knowledge production and policy relevance.
Developing robust data systems enables informed decision-making and targeted interventions.
Investing in human resources through training and mentorship ensures long-term research sustainability.

Key Action: Fund national research centers, digital infrastructure, and research fellowships.

References: Papua New Guinea Science and Technology Council Secretariat (PNGSTCS). (2016). UNESCO. (2017), World Bank. (2020).

5.5.2 Fostering Collaborative Platforms and Multi-stakeholder Involvement

Inclusive platforms ensure coordinated development and reflect diverse needs. Engagement with indigenous communities validates traditional knowledge and enhances local ownership.

Key Action: Institutionalize multi-stakeholder working groups with representation from government, civil society, academia, and indigenous leaders.

References: United Nations Development Programme (UNDP). (2019), Nakashima, D., McLean, K. G.,Thulstrup, H. D., Ramos Castillo, A., & Rubis, J. T. (2012).

5.6 Knowledge Translation and Communication

Media, policy briefs, and local-language outreach increase the accessibility of research findings. Effective communication fosters policy uptake and community-level action.

Key Action: Develop science communication units to translate evidence into targeted messaging for different audiences.

References: World Health Organization (WHO). (2012), Lavis, J. N., et al. (2003).

5.6.1. Policy Development and Institutional Reforms

Dedicated policy-research interface units promote evidence-informed governance. Institutional reforms should embed research into national planning and budgeting systems.

Key Action: Create “Science-Policy Interface Units” within planning and development ministries.

References: Organisation for Economic Co-operation and Development (OECD). (2020), Global Development Network (GDN). (2014).

5.6.2 International and Regional Partnerships

Leveraging global and regional networks brings technical support, funding, and shared learning. Participation in Pacific-wide research and policy platforms enhances PNG’s capacity.

Key Action: Expand engagement with the Pacific Islands Forum, ADB, and bilateral partners.

References: Pacific Islands Forum Secretariat. (2021), Australian Aid (AusAID). (2012).

5.6.3 Emphasizing Indigenous Knowledge Integration

Indigenous knowledge enriches ecological management, disaster resilience, and community health. Policy and research frameworks should ensure respectful integration and cultural sensitivity.

Key Action: Establish protocols for knowledge co-production and protect traditional knowledge rights.

References: Berkes, F. (2012), UNESCO. (2017).

6. POLICY RECOMMENDATIONS AND PRACTICAL STEPS

Integrating science into policy-making is crucial for informed decision-making and sustainable development in Papua New Guinea. The Papua New Guinea Science and Technology Council has recognised these aspects as critical gaps between science and policy integration processess and therefore attempts to address these through the recommendation and practical steps that follows..

6.1 Short Term Recommendation

Establisment of Liasion bodies across the science and technology landscape plays an important role of communication, translation and adoption of science policy intergration. Ansell and Gash (2008) show in the work on, 'Coping with the Challenges of Working Across Boundaries'. The study show that establishment of liasion bodies create dedicated teams to facilitate communication and coordination among scientists, policymakers, and community stakeholders. This approach is grounded in the success of similar models, as seen in Collaborative Governance. Decision are depended on good data data system where reliable data collection and management systems are decveloped. Accurate data is vital for effective decision-making, as emphasized in "Data-Driven Policy Impact Evaluation" by Imbens and Wooldridge (2009).

Long-term Strategies Amongst other things, Georgehiou et.al (2014) note that scientific research requires massive resources, and a steady funding flow as critically important leverage in the sustenance of scientific inquiry. Good funding strategies for scientific enquiries can play an important part. In addition, human skill and talent for science is also very important, and therefore must be supported with good investment in education and capacity building programs. Gillard and (2010) observes the need for strengthening educational infrastructure to cultivate skilled personnel to build research capacity in developing countries as very important. Role of Stakeholder including government, academia, industry and communitiesn is also an important part of the longer term sustainability and scientific research outcomes. Government role including providing policy support, funding, and regulation Peters and Pierre (1998) in the productivity and sustainability of scientific research work. The Academia provide focus on research, training, and knowledge dissemination, (Zomer and Benneworth, 2011). Communities and industry engage in decision-making and provide feedback, aligning with principles from "Participatory Development: The Role of Community Participation in Development Planning and Project Management" by Cohen and Uphoff (1980).

Monitoring and Evaluation – Regular Monitoring provides an important role in the scientific research process and includes evaluation of systems for policies and research programs (Rossi, Lipsey, and Freeman (2004). Adaptive Management provides opportunity to adjust strategies based on evaluations, as recommended in "Adaptive Management of Natural Resources: Theory, Concepts, and Applications" by Williams and Brown (2012). Together with these suggested action steps may include, stakeholder meetings to build trust. Create data-sharing playtforms to enhance transparency. Organise training workshop to boost skill and engage local communities in pilot projects for feedback. While collaboration is emphasized, some argue for independent research initiatives to drive innovation without policy constraints. However, integrating such findings into mainstream policy can face challenges, as noted in "Bureaucracy and Innovation" by Downs (1967). By adopting these strategies and involving all stakeholders, Papua New Guinea can effectively integrate science and policy for sustainable development.

7. CONCLUSION

In conclusion, the integration of science and policy is vital for Papua New Guinea to navigate its unique developmental challenges effectively. The current landscape of science and policy in Papua New Guinea presents both challenges and opportunities. Significant advancements have been made in scientific research across various sectors; however, data availability remains a pressing issue, especially for local communities reliant on this information for sustainable practices. To improve the effectiveness of policies concerning environmental management, health, agriculture, and climate change, Papua New Guinea must prioritize the development of solid data collection systems, increase funding for research, and encourage partnerships between government,

academia, and civil society. Future initiatives should concentrate on building local capacity for scientific research, ensuring that scientific findings are translated into actionable policies that benefit both communities and the environment. By bridging the gap between knowledge and action, PNG can foster more informed and resilient decision-making processes that support sustainable growth and environmental stewardship. Such integration not only enhances the country's capacity to manage climate change, natural resources, and social development but also promotes resilience in the face of uncertainties. Moving forward, it is imperative to adopt committed, inclusive, and locally tailored strategies that empower diverse stakeholders and leverage indigenous knowledge alongside scientific insights. Only through such collaborative and adaptive approaches can PNG realize its development vision and ensure a sustainable future for all its communities.

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Postgraduate Education at Papua New Guinea University of Technology: A Distinctive Journey of Achievements and National Development

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Abstract: In celebration of 50 years of Papua New Guinea's independence, Papua New Guinea University of Technology (PNGUoT) reflects on its pioneering role in spearheading national development through postgraduate education. PNGUoT has shaped experts and researchers in key Science, Technology, Engineering, and Mathematics (STEM) fields pivotal to the socio-economic development of the country. The purpose of this article is to evaluate PNGUoT's accomplishments in teaching and research excellence, and to explore future developments that will establish it as a knowledge hub. The university has made significant progress, but it remains constrained by ongoing funding limitations, gaps in physical infrastructure, equipment, and laboratory facilities, and inadequate scholarship coverage. This constrains the drastic expansion of postgraduate training necessary for industrialization, innovation, and a knowledge-based economy. Between 1976 and 2025, PNGUoT graduated 28 Doctor of Philosophy, 451 Master's, and 210 Postgraduate Diploma and Postgraduate Certificate students. Between 1976 and 2000, the number of graduates was 75, whereas in the subsequent 25 years, from 2001 to 2025, it significantly increased to 614. In recent years, the University has graduated approximately 40-50 postgraduate students annually, with enrolments reaching 214 in 2025 across the faculty. Despite this progress, access to postgraduate education remains limited to a small segment of the population. A significant gap exists that must be addressed to expand access and bring postgraduate programs closer to the levels seen in developed nations, involving ongoing investment in research infrastructure, academic staff capacity-building, strengthened partnership-building, and a balanced scholarship scheme. As PNG charts its next 50 years of development, the revitalization of postgraduate education in PNGUoT and other higher education institutions offers a transformative path to unlocking human capital, enhancing research quality, and fostering technological leadership to propel educational, economic, and scientific contributions to sustainable national development for all.

Keywords: higher degree research, innovations, national development. research skills

1. INTRODUCTION

In today's era of rapid technological advancement and intense global competition, postgraduate study is not a luxury—it is a necessity. Postgraduate education and research are among the most critical pathways to remain at the forefront of knowledge and technological innovation. A country's ability to adopt, disseminate, and capitalize on rapid technological progress depends heavily on the strength of its tertiary education system. Accessible, well-functioning higher education institutions and effective national innovation systems can significantly accelerate a developing country's path toward sustainable development and long-term success. A country cannot achieve sustainable economic growth and development without the use of science and technology.

Postgraduate programs (Master's and PhD) offered at universities train subject specialists, researchers, and creative pathfinder leaders who are needed to initiate the sustainable development of a country's economy and society. Qualified professionals, trained in higher degree courses, possess the potential to drive developments in fields such as agriculture, engineering, technology, social sciences, and healthcare. Postgraduates are instrumental in creating new knowledge and innovations. Their research can serve as the foundation for new products and technologies, as well as solutions to national issues such as environmental threats, climate change, and food security, thereby enhancing productivity and efficiency.

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Universities, through their postgraduate programs, can influence communities through their innovative solutions and change the lives of millions. A well-known case of an environmental problem would be in Bangladesh rural communities, where millions of people were exposed to arsenic-laced groundwater, which poses severe health issues, including skin diseases and cancer. The problem is complex, as it involves both geological and social elements. A group of researchers, comprising postgraduate students from the Bangladesh University of Engineering and Technology and Dhaka University, collaborated with international partners to conduct intensive studies on the hydrogeology of arsenic contamination. They encouraged the installation of safer tube wells in low-arsenic zones, as well as advancements in low-cost filtering systems that they developed and mass-produced for public use in partnership with multilateral agencies (Rahman et al., 2010; Jannat et al., 2022).

In this era, research in science and technology is more than just tools in any economy—they are drivers of economic prosperity, social progress, and national resilience. For conducting research, trained human resources are necessary. Nations that invest in higher education, research, innovation, and technology build strong foundations for sustainable growth and improved quality of life for their citizens (Acharya & Pathak, 2019; Li et al., 2024). PhD/Master's students develop cutting-edge innovations ready for industrial application. Postgraduates in science and technology can potentially fuel R&D efforts within industry clusters and science parks. Postgraduates often become lecturers and researchers in universities and training institutions. They are required to maintain quality teaching, develop future researchers, and build academic and institutional capabilities. The benefits of vital postgraduate education also affect the primary and secondary education systems. For example, in Finland, a Master's degree is the minimum qualification for a permanent teaching position, even in primary schools. Primary teachers undergo a five-year integrated Master's program that includes a major in teaching education and the completion of a thesis on the same academic standard as other university subjects (Sahlberg, 2013). In contrast, Papua New Guinea has been described by the World Bank as being in a "human capital crisis". Such a situation, precipitated by poorly trained teachers impacting classroom learning, could be overcome by providing structured lesson plans (Needham, 2024).

A highly educated workforce attracts investment, promotes entrepreneurship, and enhances the country's global competitiveness. Postgraduate training develops expertise in areas such as public health, environmental studies, economics, and governance, enabling the design of better policies and the provision of higher-quality services. Higher degree training develops critical thinkers with problem-solving abilities and innovators, effectively creating a strong pipeline for entrepreneurship and research and development (R&D). This, in turn, makes the nation an attractive destination for investors, helping industries evolve and flourish in the rapidly changing global economic landscape (Abramo et al., 2019). This study is undertaken with the following objectives: i) To evaluate the impact of PNGUoT's postgraduate education in STEM fields on national development between 1976 and 2025; and ii) To identify and promote key strategies for addressing the challenges and gaps that constrain the expansion of postgraduate training within the broader postgraduate education ecosystem in Papua New Guinea.

2. METHODOLOGY

This study deploys a mixed-methods design, combining quantitative and qualitative approaches, grounded in secondary data analysis to evaluate the contributions, status, and challenges of postgraduate studies at the Papua New Guinea University of Technology (PNGUoT) during the period 1976-2025.

2.1 Data Sources

Institutional Records and Reports: Postgraduate enrollment and graduation statistics were obtained from official academic records, annual reports, and strategic papers of PNGUoT to account for trends and performance during the research period. National Government policy documents, including the Medium-Term Development Plan IV and Vision 2050, were studied to position the role of postgraduate education in national development agendas. Information on funding levels, scholarship programs, and infrastructural capacities was collected from newspapers and Government budget documents. Published literature and comparative international education data, i.e., Organization for Economic Cooperation and Development (OECD) postgraduate benchmarks, were reviewed to contrast the postgraduate education situation in PNGUoT with global standards.

2.2 Data Analysis and Synthesis

Quantitative enrollment and graduation data were scrutinized to establish trends in growth, capacity thresholds, and the efficiency of output from postgraduate programs. Qualitative content analysis of policy documents revealed strategic imperatives and challenges pertinent to the expansion of postgraduate education. The study integrated these data to identify gaps, limitations, and opportunities, particularly in funding, infrastructure, and scholarship coverage. Projections and recommendations were made by integrating institutional data with national strategic goals and international standards to advise paths to rejuvenate postgraduate education at PNGUoT.

2.3 Limitations and Ethical Considerations

The study relies on secondary data, which may have discrepancies and gaps, and the projections assume continuation of current policies and funding levels, which may vary. All data sources are publicly available or presented in institutional reports; therefore, the study is compliant with the ethical criteria of confidentiality and data standards of use.

3. STATUS OF HIGHER DEGREE TRAINING IN PNG

Overall, there is a lack of openly available information on the number of postgraduate students enrolled in Papua New Guinea. The major public universities—namely the University of Papua New Guinea, PNG University of Technology, and the University of Goroka—have established postgraduate schools or faculties. Newer universities such as IBS University, Sonoma Adventist College, and PNG University of Natural Resources and Environment (PNGUNRE), along with private institutions like Divine Word University and Pacific Adventist University, may enrol only a handful of postgraduate students.

Since independence, Papua New Guinea has largely overlooked the importance of capacity building and higher degree training of local researchers, despite its direct relevance to the realization of the country's national goals and directive principles (Baje & Itaki, 2022). It has been argued that the current capacity is insufficient even to meet the academic staffing needs of the country's expanding higher education sector. The present output of doctoral graduates from both national institutions and aid-supported programs remains inadequate to meet future demand (Baje & Itaki, 2022). A recent estimate suggests that 22 PhDs and 504 Master's degrees were awarded through domestic postgraduate training within Papua New Guinea institutions between 2012 and 2016 (Kaupa et al., 2024). The study highlights that, despite growing investment in human and financial resources for research and development (R&D), the current levels remain meagre and insufficient. Furthermore, the training of young researchers at the Master's and PhD levels—and retaining them across various research fields—is seen as a crucial first step in ensuring that PNG develops an adequate pool of qualified R&D personnel at the national level (Kaupa et al., 2024).

4. HISTORICAL PERSPECTIVES OF POSTGRADUATE PROGRAMS AT PNGUOT

The Papua New Guinea University of Technology (PNGUoT), since its inception in 1973, has taken a strategic decision not merely as a higher teaching institution, but has also decided to integrate teaching and research. The critical element for such a decision was not only to become a higher learning institution of excellence in teaching and research, but also to meet the professional and developmental needs of the young nation by building local human capacity. The reflection of such a decision was the graduation of its first PhD in Civil Engineering and one MCOM student from the Department of Accountancy and Business Studies in 1976. This trend continues into the later years. However, most of the postgraduate students were initially overseas academics at the university. The program was unable to attract any national staff/students into the postgraduate program until 1981, when three of them enrolled for the postgraduate diploma. Between 1976 and 2000, the total number of PhDs awarded was 9, the number of Master's was 21, and PGD/PCert was 45 (Figure 1a).

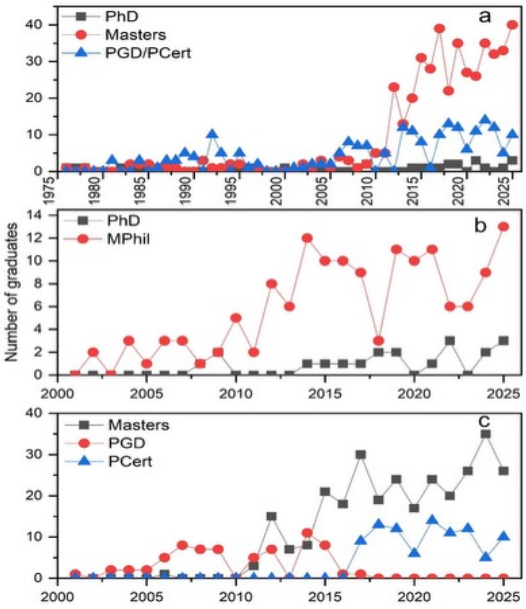

Figure 1. Growth of postgraduate programs at PNGUoT: a) Graduation trend from 1976-2025. b) Graduation trend in Research only programs from 2001-2025 (PhD, MPhil). c) Graduation trend in course-based programs from 2001-2025 (Masters-Master of Science/Engineering/Technology/Communication Studies/Business Administration, etc., PGD, and PCert programs).

The momentum of postgraduate studies did not continue for long. PNGUoT could not take advantage of the generous funding for a sustainable postgraduate program and research through institutionalizing the postgraduate programs, foreseeing the importance from the standpoint of human capacity building and succession planning. The postgraduate programs were mostly in hibernation during the 90s to early 2000s. This was primarily due to the mass exodus of experienced staff with postgraduate supervision capability, resulting from the floating and depreciation of the PNG Kina. PNGUoT reached a crisis point in terms of recruiting and retaining qualified staff. This prompted PNGUoT to reconsider the strengthening of in-house postgraduate studies and research. With the change of time, technological development, and experience, the university embarked on "UNITECH 2030", Papua New Guinea University of Technology's Pathway to the Future, to align its focus and direction with the Government policies, like Vision 2050, DSP 2030 with the strategic development goal of promotion of scholarships, externalization of academic programs, and entrepreneurial quality development.

From the mid-2000s, postgraduate programs underwent rejuvenation through a refocusing on research and scholarship character development, as well as the reintroduction of the Graduate Assistantship Program (GAP) in place of the Assistant Lectureship Scheme in 2001 to promote scholarship character and strengthen the in-house program targeting the first-degree holder with excellent academic records to pursue Master's and PhD (Figure 2b and 2c). The GAP became a cornerstone of PNGUoT's efforts to build a robust research culture, particularly by integrating research training with academic staffing needs.

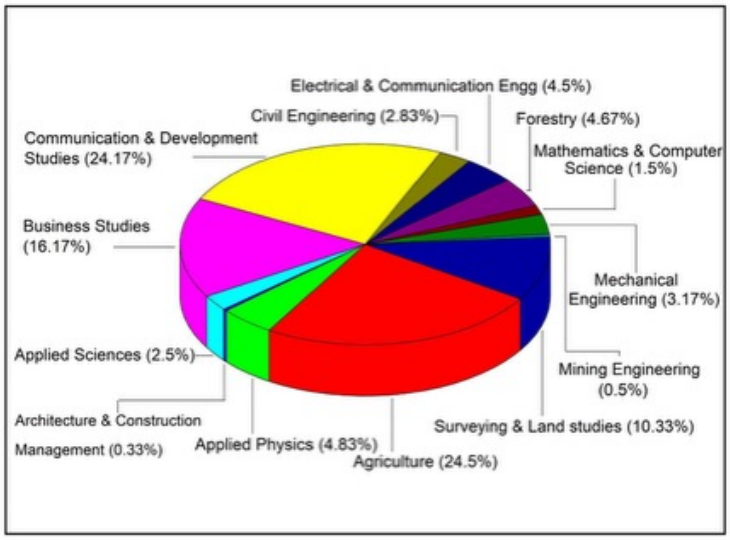

Figure 2. Contribution of PNGUoT academic schools to the postgraduate program outputs (2001-2025)

A major catalytic shift in the in-house program occurred through the Australian Centre for International Agricultural Research (ACIAR)'s postgraduate scholarship scheme, coordinated by the University of Queensland (UQ), which was allocated to the Department of Agriculture between 2005 and 2011. ACIAR supported postgraduate students pursuing Postgraduate Diplomas in Agriculture and Forestry to research topics aligned with in-country ACIAR projects. The ACIAR Scholarship Scheme aimed at strengthening capacity building and training the supervisors was highly successful by graduating five Master's and 35 postgraduate diploma students.

This initiative demonstrated the value and impact of collaboration between International academic institutions and the National Agricultural Research and Extension system. In addition, Academic Departments such as Agriculture, Surveying and Land Studies pioneered collaboration with industries to fund postgraduate student research. Trukai Industries Ltd – Rice Research Scholarships, which have been funded since 2012, have supported over 13 postgraduate students from the School of Agriculture at PNGUoT (Trukai Industries Ltd., 2024). Additionally, the Agriculture Department partnered with several key organizations, including the National Agricultural Research Institute, Ramu Agri Industries Ltd, the Oil Palm Research Institute, the New Zealand Government-supported Scholarship Program "Women in Agriculture (WAG)", and the Morobe Provincial Government Scholarships, to support staff and students in their postgraduate studies. The Agriculture Department took full advantage of these available scholarships (Figure 2). It was at the forefront in terms of postgraduate studies and research, thanks to sustained leadership, effective teamwork, and the recruitment and retention of qualified staff from the home-grown postgraduate program. The Department quickly became the role model for other academic departments to

reinvigorate their postgraduate programs and attract students.

4.1 Postgraduate School

At the initial stages, postgraduate programs were delivered through individual academic departments, often with limited centralized coordination. The Postgraduate/Higher Degree Committee of the Academic Board was mandated to administer the postgraduate program through the Registrar's office. By the early 2000s, it became increasingly evident that a more integrated and coordinated approach was needed. During this period, postgraduate education was also recognized as essential for addressing staffing needs within the university and other national institutions. The increasing number of students across the academic departments necessitates the need for a centralized coordinating body to maintain quality and steer postgraduate studies and research programs to achieve their intended objectives. PNGUoT approved the creation of the Postgraduate School in 2006, headed by a Dean.

The appointment of the Dean materialized only in 2013 with the objectives to:

i. Promote, administer, and oversee the implementation of the postgraduate policy and activities throughout the university.
ii. Formulate and oversee the implementation of the comprehensive research policy and guidelines to facilitate a vibrant research culture and capacity building to foster research outcomes that would benefit the nation of Papua New Guinea and humanity as a whole.
iii. Publicize and market the Postgraduate programs and the research strength of PNGUoT to the broader community
iv. Establish linkages and develop partnership programs within and outside of PNG.

In 2023, the Postgraduate School was renamed as the Faculty of Postgraduate Studies, Research and Innovation, and aligned with the Strategic Plan 2025-2029 for academic excellence and conducting state-of-the-art research leading to innovation and product development. To underscore its importance, Research, Development, and Innovation was designated as one of the four strategic pillars of the 2025–2029 Strategic Plan. In addition, a high-level committee—the Research, Innovation, and Development Team (RIDT)—was established in 2025 under the Postgraduate Studies, Research, and Innovation Committee to spearhead innovation efforts.

4.2 Internationalization

With recent progress in postgraduate programs, PNGUoT started working towards internationalization of her programs to integrate an international, intercultural, or global dimension into the purpose, functions or delivery for global competition for talents, recruitment of international students, students, staff and scholars exchange programs, internationalization of the curriculum, and research and education partnership between institutions regionally and internationally. This, in turn, will provide a competitive advantage in terms of innovation, maintaining a high level of quality, being committed to corporate and social responsibility, and continuing to strive to provide the best education while adapting to different countries and cultures. Through student and staff exchanges, partner universities will benefit from each other's experiences, best practices, and innovative approaches, ultimately building partnerships for collaborative research and supporting partnerships that enhance interpersonal skills and job prospects.

As part of its internationalization efforts, PNGUoT initiated a partnership in 2012 with the Caribbean and Pacific Island Mobility Scheme (CARPIMS), Building University Links for Action (BULA), and the Associate Partners with DREAM-ACP and KITE projects, all funded by the European Union under ERASMUS Mundus. About 29 PNGUoT students and staff benefited under the EU-funded projects, while PNGUoT also hosted 19 staff and students from various Pacific Islands, Caribbean, and African countries. PNGUoT is also a member of the Association of the Commonwealth Universities (ACU) and every year hosts one student under the Queen Elizabeth Commonwealth Scholarship Scheme (QECS). PNGUoT is also the signatory of the Magna Charta Universitatum, and a member of the Pacific Islands Regional Network (PIURN). The university also has ERSAMUS-Plus partnerships with universities in Portugal, Spain, Hungary, and Romania. PNGUoT has bilateral agreements with universities in Australia, New Zealand, India, China, the USA, Fiji, and Tonga. The university has now created the Office of Strategic Internationalization to coordinate and gauge strategic partnerships.

4.3 Postgraduate Student Research Seminar

To showcase the achievements of postgraduate studies and research, the postgraduate student research seminar was introduced in 2011. It has since become an annual event that highlights the postgraduate studies and research capabilities, communication, and presentation skills of the postgraduate students. The seminar aims to promote the development of a research culture at PNGUoT and PNG. Every year, on average, more than 50 postgraduate students present their research on a wide range of vital areas that contribute positively to PNG's society and economic development. University academics, students, staff, and other

stakeholders from the related organizations/institutions attend this annual event. It has become a hallmark event for PNGUoT. Participants and attendees have included representatives from National Agricultural Research Institute, Department of Agriculture and Livestock, University of Natural Resources and Environment, Australian Centre for International Agricultural Research, Department of Foreign Affairs and Trade (Australia), Institute of Medical Research (Papua New Guinea Institute of Medical Research), Fresh Produce Development Agency, PNG Forest Research Institute, and PNG Research, Science and Technology Secretariat, among others.

Figure 2 illustrates a summary of postgraduate graduation trends by school for the years 2001 to 2025, as well as the proportional contribution of each academic unit to the total output of 600 graduates over the period. The School of Agriculture and the School of Communication and Development Studies were the leading performers, with each contributing approximately 25% of the overall postgraduate completions. This reflects their stable enrollment and program offerings over the years. The School of Business Studies contributes 16.2%, and the School of Surveying and Land Studies contributes 10.3%. A closer examination reveals that in the School of Communication and Development Studies, the majority of the graduates (92 out of 150) earned a Postgraduate Certificate in Student Centred Teaching. Only 36 students earned higher degrees, such as the Master of Communication Studies or the Master of Arts in Organizational Leadership. This indicates that shorter skill-based certification programs tremendously pad the number of graduates for that school. The remaining schools, although diverse in their academic disciplines, contributed less than 5% to the overall postgraduate output. These figures reveal a concentration of postgraduate activity within a small group of schools, with others making a minor contribution to postgraduate education during the period under review.

Variation in postgraduate training performance across university departments/schools is well-documented in the literature, particularly in the developing world. Strong academic leadership and institutional infrastructure are crucial for facilitating prompt progress and the completion of postgraduate studies (Lee, 2008). The availability of aptly qualified and research-active supervisors bears a direct correlation with student achievement, as inadequate supervision is a well-documented barrier to the completion of postgraduate studies (McCallin & Nayar, 2012). Research culture of organizing regular seminars, publications, and inter-institutional collaboration generates a lively climate for intellectual debate among researchers and students' motivation (Manathunga, 2005). Fostering adequate infrastructure and providing laboratory equipment, as well as financing, are also required to develop research work, especially in science and engineering domains (Altbach et al., 2009). Programs and research integrated with national development priorities and industry needs attract higher enrolments and external partnerships, resulting in sustainable learning environments (Teferra & Altbach, 2004). Student support structures—namely, well-delineated timelines, progress tracking, and administrative efficiency—are shown to reduce attrition and increase completion rates (Wisker, 2003). Without these conducive conditions, postgraduate training is usually characterized by delays, low enrolments, and extensive dropouts.

5. CURRENT STATUS OF POSTGRADUATE PROGRAMS AT PNGUOT

The Papua New Guinea University of Technology (PNGUoT) boasts a diverse and rich portfolio of postgraduate courses, comprising course-based, research-based, and professional development programs, offered through regular and flexible delivery modes. The Faculty of Postgraduate Studies, Research & Innovation manages approximately 64 programs, including 22 PhDs, 40 Master's degrees, and a couple of postgraduate certificate programs. Some Master's degrees, such as those in Remote Sensing and GIS, are offered via distance learning mode. Research-only options include MPhil and PhD degrees across various fields (e.g., sciences, engineering, humanities, and the built environment). Course-based and executive programmes (e.g., MBA, EMBA) cater to the professional and practical needs of individuals. This mix ensures access, flexibility, and a range of disciplines.

The enrolment statistics for Semester 1 of 2025 are presented in Table 1. The postgraduate student enrollments stood at 214 students, comprising 139 male students (65%) and 75 female students (35%). Among the 192 Master's-level postgraduate students, approximately 128 students (67%) have opted for course-based Master's programs, while the remaining 33% have opted for research-only programs (MPhil). These data exclude enrolments for Semester 2, 2025, online Master's programs, and admissions through nominations. This observation aligns with the findings of Vieno et al. (2022).

Table 1. Enrolment data for Semester 1 of the academic year 2025

	Female			Male			
Schools	Course-based programs	MPhil	PhD	Course-based programs	MPhil	PhD	Total
Agriculture	8	4	2	7	7	5	33
Applied Physics	1		3	4	2		10
Applied Sciences	2	1	1	1	2	1	8
Architecture & Construction Management	9	1		2	2		14
Business Studies	20	3		40	5	2	70
Civil Engineering		3	1	8	2		14
Communication and Development Studies	2			2			4
Electrical and Communication Engineering		2	1		11	3	17
Mathematics and Computer Sciences	8			8	4	3	23
Mechanical Engineering				6			6
Mining Engineering		1			3		4
Surveying and Land Studies		2			9		11
Total	**50**	**17**	**8**	**78**	**47**	**14**	**214**

Course-based postgraduate programs are more popular than research-based programs due to their structured syllabus, shorter duration, and profession-oriented nature. They impart practical knowledge in coordination with industry standards, making them popular among professionals who do not want to advance without conducting research in academia. They have more structured schedules, broader accessibility, and relatively lower costs, making them appealing to students from diverse backgrounds. On the other hand, research-only degrees require strong research skills, self-motivation, and a higher level of commitment, which may not be suitable for all students. With the heightened global need for job-ready graduates, course-based degrees offer immediate employability and flexibility, making them the preferred choice in most professional and academic settings.

The statistics on postgraduate studies completion in 2025 are presented in Figure 3. A total of 53 students graduated with postgraduate degrees. Of them, 26 students received course-based degrees (49%), thesis-based Master's students comprised 14 students (26.4%), and 10 students (18.9%) obtained postgraduate certificates in Student Centred Teaching. Three students completed their PhD degrees.

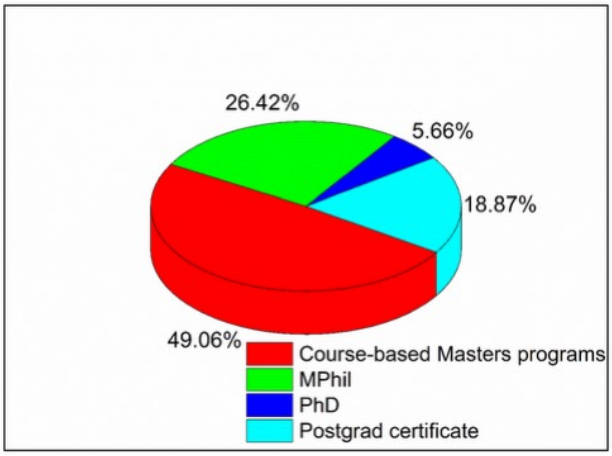

Figure 3. The composition of the postgraduate cohort graduated in 2025.

6. CONTRIBUTIONS TO THE NATIONAL DEVELOPMENT OF PNG

Overall, the PNGUoT postgraduate programs have contributed 28 PhDs, 451 Master's, and 210 Postgraduate Diploma/Postgraduate Certificate graduates between 1976 and 2025. Between 1976 and 2000, only 9 PhD, 21 Master's, and

45 PG Diploma/PG Certificate students graduated. However, during the following 25-year period from 2001 to 2025, the number increased significantly to 19 PhD, 430 Master's degrees, and 165 PGD/PG Certificates. In developed countries such as the USA, important social indicators like individual and household income have been significantly influenced by educational attainment (Wang, 2023). PNGUoT postgraduates and their studies served as a successful conduit for technology transfer to local industries. We conceptualize that their contribution towards national development goals is multifaceted, and they serve as a direct link to industries (Figure 4).

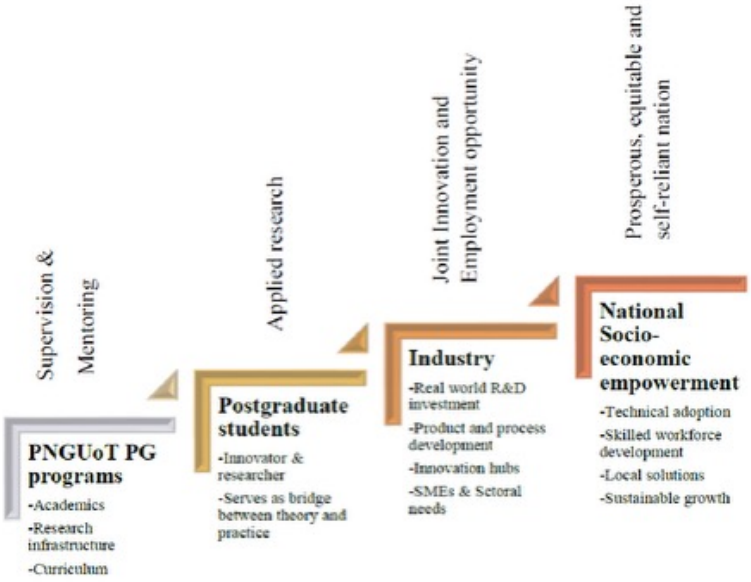

Figure 4. Conceptual framework illustrating contributions of expanding postgraduate programs to national development

During the learning process, students will design innovative prototypes, processes, or systems tailored to the local context. Engineering students can design and develop low-cost, locally accepted machinery suitable for small and medium-sized enterprises (SMEs). In contrast, ICT students may develop custom data systems for logistics firms, agribusinesses, or Government agencies. Environmental science postgraduates might improve renewable energy proposals in rural areas. Such research findings are directly accessible to local industries and funding agencies, reducing dependence on expensive overseas technologies, promoting local innovation, and enhancing efficiency in key economic sectors, including agriculture, manufacturing, logistics, and mining. The scant data available on domestic postgraduate training status within PNG suggest that the total number of postgraduates (Masters and PhDs) trained through research between 2012 and 2016 stands at approximately 526 (Paula et al., 2024). The postgraduate output between 2012 and 2016 from PNGUoT alone was 118, accounting for 22.4% of the nation's postgraduate output.

One of the key strengths of postgraduate research is that it focuses on solving local problems. If students conduct studies that are rooted in the realities of their context, they can gain valuable insights. In that case, the solutions proposed are also likely to be more practical and culturally appropriate than those derived from overseas models. Applied Sciences students can devise solutions to address sanitation or malnourishment in rural communities, agricultural researchers can develop pest-resistant or climate-resilient crops, and social scientists can design models of participatory governance. Such research enhances service delivery, fosters public trust in academia and science, and promotes community resilience. Postgraduates play a crucial role in developing skilled human capital. Beyond their research output, they become lecturers, advisors, policymakers, and innovators in their respective fields. Their presence in universities, government agencies, NGOs, and R&D institutions adds intellectual depth to the nation. With their specialization in critical thinking and orderly approach to problem-solving, they guide policy directions and enhance the quality of national research and development priorities.

Lastly, postgraduate research fosters the inclusive and sustainable development of PNG. Addressing local challenges, creating new economic opportunities, and reinvigorating public and private institutions enables development benefits to extend to marginalized and rural communities. Research on gender inclusion, indigenous knowledge, and community-based programs aligns scholarship with national agendas and the UN Sustainable Development Goals (SDGs), thereby fostering an inclusive and sustainable approach to economic growth**.**

7. FUTURE OUTLOOK

At PNGUoT, the success of the postgraduate program is directly attributable to three mutually dependent drivers: the Graduate Assistance Program (GAP) scholarship, effective academic and administrative management, and quality supervision (Akanda

et al., 2013). The GAP scholarship is a critical variable in making access feasible and ensuring student retention by funding tuition fees and living allowances. This aid reduces dropout levels, allowing students, particularly those who are disadvantaged, to focus solely on their studies. Of similar importance is the role played by proper program and administrative management. Those schools with clearly established postgraduate policies, timely approval procedures, and integrated progress-monitoring systems are more apt to provide smoother student progression and completion. The third pillar of success is academic supervision. Regular interaction, encouraging feedback, and shared research interests between supervisors and students are critical to academic progress and timely completion. Experienced, research-active supervisors create a successful research environment, and unsatisfactory supervision has consistently been linked to attrition. These findings are consistent with more universal postgraduate success criteria, which focus on scholarship (Altbach et al., 2009), institutional support (Wisker, 2005), and supervisor quality (Lee, 2008; McCallin & Nayar, 2012) as key drivers of postgraduate performance. The Higher Education Loan Program (HELP) introduced by the PNG Government in 2022 is also a step in the right direction to encourage postgraduate studies and ease the financial burden on self-sponsored students.

Further support and promotion of postgraduate education are required within the country. Expanding access to higher education aligns with UNESCO's aim of developing inclusive and equitable quality education to achieve the fourth Sustainable Development Goal of the UN (Li et al., 2024). Promoting postgraduate education plays a crucial role in shaping a country's human resource development, as well as driving scientific and technological innovation—both key to economic growth. In developed countries such as the USA, important social indicators like individual and household income have been significantly influenced by educational attainment (Wang, 2023). Popularization has the potential to attract students from neighbouring countries through various government exchange programs and existing networks. Such transnational popularization and branding will enhance regional stability in all possible spheres —social, financial, trade, and resource sharing.

Table 2 provides an example of the postgraduate enrolments required for Papua New Guinea, benchmarked against OECD standards.

Table 2. Estimates of postgraduates required to match the benchmarks of OECD countries

	Target percentage of the 25-34 age group	OECD benchmark enrolments/y	Modest national targets (10% of benchmark)
Masters	10-15%	175,000–262,500	17,500–26,250
PhD	0.5-1.0%	8,750–17,500	875–1,750
Total	-	183,750–280,000	18,375–28,000

Papua New Guinea's target population for postgraduate education is approximately 1.75 million people, representing the 25–34 age group within a total estimated population of 11 million (United Nations, Department of Economic and Social Affairs, Population Division, 2023). According to OECD benchmark standards, 10–15% of this age group should be enrolled in Master's programs, and 0.5–1% in PhD programs. This translates to approximately 175,000–262,500 Master's enrolments and 8,750–17,500 PhD enrolments annually. Even assuming a more modest target of 10% for Master's and PhD studies, given PNG's current funding constraints, at least 17,500–26,250 Master's and 875–1,750 PhD annual enrolments are required. These figures highlight a significant gap between current enrolments and the scale of postgraduate education capability needed to meet the industrial and developmental aspirations of a modern PNG.

The need for horizontal and vertical expansion of postgraduate programs poses significant challenges to Higher Education Institutions, including PNGUoT. Much of the government's emphasis is on increasing the limited space available at undergraduate programs, and efforts are directed at increasing the number of students. These increases will put additional stress on existing manpower eligible to mentor and advise postgraduate students. Currently, the annual cost of training a STEM Master's student (MSc, MTech, or MEngg) at PNGUoT is PGK 44,150, while the cost for a PhD student on a full scholarship is approximately PGK 54,667. To enrol and train 500 Master's and 50 PhD students in the first year, and gradually scale up to 1,000 Master's students by the second year and 150 PhD students by the third year, PNGUoT would require a total funding outlay of PGK 24.81 million in Year 1, PGK 49.62 million in Year 2, and PGK 52.35 million in Year 3. This level of funding must be sustained in the future.

Research infrastructure and laboratory facilities are central components of quality postgraduate education, particularly for Master's by research and PhD qualifications. They are the foundation for practical training, quality data generation, and innovation, enabling students to conduct proper research and produce original theses. Effective labs influence the quality of supervision, academic honesty, and research productivity, all of which are central to program accreditation and

global competitiveness. In addition, equipped laboratories draw research grants, facilitate industry collaborations, and enable inter-school cooperation. The establishment cost for research labs varies across disciplines, ranging from PGK 500,000 to 1.5 million for mid-level research laboratories and PGK 5 million or more for advanced research facilities. For a university like PNGUoT, anticipating the growth of postgraduate training in at least 5–6 priority disciplines, an initial capital outlay of PGK 13–15 million would be necessary to establish common core laboratories, discipline-specific research facilities, and an ICT/data analytics centre. Planning should also allow for sustainable inputs, such as maintenance, personnel, and security/safety systems.

Scholarships are essential to developing postgraduate programs by enabling equitable access, attracting high-quality candidates, and allowing full-time dedication to study and research. In a context like Papua New Guinea, where many potential postgraduate students are financially disadvantaged, scholarships are necessary if a strong national research capacity is to be developed and skills shortages in key areas are to be addressed (Altbach et al., 2009; Salmi, 2017). Scholarship provision reduces student attrition, increases completion rates, and helps universities recruit talented graduates into academic and research careers. To maintain a thriving scholarship ecosystem, financing can be achieved through a combination of government appropriations, competitive research grants, development partners (such as the Asian Development Bank, Department of Foreign Affairs and Trade (Australia), and the European Union), and institutional programs (World Bank, 2010). The universities also establish endowments or cost-sharing arrangements with industry and public sector organizations needing research-informed solutions. A structured national postgraduate fellowship program, supported by partnerships and aligned with national development priorities, can significantly enhance the capacity and quality of postgraduate education (UNESCO, 2015).

8. CONCLUSIONS

As Papua New Guinea marks 50 years of independence, the Papua New Guinea University of Technology (PNGUoT) stands as a national icon of technical and scientific advancement. Over the decades, PNGUoT's postgraduate programs have significantly contributed to the development of human capital in key sectors such as engineering, agriculture, environmental science, and information technology—critical to realizing the nation's development aspirations.

Despite these achievements, postgraduate education at PNGUoT and other higher education institutions faces persistent challenges, including inadequate funding, limited laboratory facilities, and the absence of a systematic scholarship support framework. Nevertheless, the vision and goals outlined in the Medium-Term Development Plan IV and Vision 2050 call for a substantial scale-up in the training of Master's and PhD graduates to meet the demands of a modern economy, climate resilience, digitalization, and industrialization.

Looking ahead, PNGUoT must position its postgraduate programs as engines of innovation and policy influence, underpinned by strategic investment, robust academic partnerships, and alignment with national development priorities. Bridging the current capacity gap will require a coordinated effort by the government, development partners, industry, and the university to build a sustainable and effective postgraduate training ecosystem—one capable of shaping the next 50 years of nation-building in Papua New Guinea.

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Retrospective Screening of Cattle Serum for Leptospirosis in the Morobe Province of Papua New Guinea

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Abstract: Leptospirosis is a significant bacterial zoonosis affecting both animals and humans across tropical regions, including Papua New Guinea (PNG). In cattle, this disease can cause abortion, decreased milk production, high fever, jaundice, and reddish-brown urine discoloration, resulting in substantial economic losses for livestock producers. This study, part of an ongoing PhD research investigating leptospirosis epidemiology in PNG livestock, retrospectively analyzed 902 cattle serum samples from 19 farms in the Morobe Province using real-time PCR (qPCR). These samples, originally collected in 2017 through a collaborative NAQIA project and stored at -80°C at PNGIMR, were accessed in 2022 for qPCR. Despite previous documentation of *Leptospira interorgans* serovars Hardjo and Tarassovi in PNG cattle, all samples tested negative for *Leptospira* spp. This unexpected outcome may potentially reflect prior vaccination practices in the sampled herds, though vaccination records were unavailable. This finding has prompted further investigation of presumed non-vaccinated cattle farms in subsequent chapters of the PhD project to better determine the true prevalence of leptospirosis in PNG. Nevertheless, this investigation provides valuable baseline data on cattle distribution, breed characteristics, and farm management practices in the Morobe Province that will inform the broader PhD research framework on leptospirosis epidemiology in PNG, contributing to improved animal health surveillance strategies and zoonotic disease control measures.

Keywords: Cattle disease, Real-time PCR, Retrospective serum, Cattle farms, Leptospirosis epidemiology

1. INTRODUCTION

Leptospirosis is a widespread zoonotic disease caused by pathogenic spirochetes of the genus *Leptospira*, affecting both humans and animals globally with high prevalence in tropical regions (Adler 2015; Costa et al., 2015). In cattle, infection with pathogenic serovars, especially *Leptospira interorgan* serovar Hardjo, manifests as abortion, decreased milk production, fever, jaundice, and hemoglobinuria (Bomfim et al., 2008; Hashimoto et al., 2017; Zelski 2007). The economic impact on livestock production in tropical countries, including Papua New Guinea (PNG), is substantial due to reproductive losses and decreased productivity (Carvalho et al., 2024; Robi et al., 2024). Clinical presentations often resemble other bacterial and viral infections, necessitating laboratory confirmation for accurate diagnosis (Bande et al., 2014; Shagfigi et al., 2014).

Control strategies for bovine leptospirosis encompass vaccination, strategic antibiotic treatment, and environmental management (Mwachui et al., 2015; Ellis 2015). Vaccination against common serovars forms the cornerstone of prevention (Hartskeerl et al., 2011), while prophylactic antibiotic therapy with streptomycin or tetracyclines can reduce urinary shedding in carrier animals (Subharat et al., 2012). Environmental measures focus on limiting exposure to contaminated water and reducing contact with wildlife reservoirs, particularly rodents that serve as maintenance hosts for various serovars (Boey et al., 2019; Mwachui et al., 2015). In regions like PNG with limited systematic control programs, understanding the

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epidemiological landscape remains essential for developing effective intervention strategies (Wynwood et al., 2014).

Diagnostic techniques for leptospirosis include serological and molecular methods with varying sensitivity and specificity profiles (Picardeau 2013; Musso et al., 2013). Serological approaches, such as microscopic agglutination test (MAT) and enzyme-linked immunosorbent assay (ELISA) detect antibodies in blood serum, with MAT considered the gold standard despite requiring specialized facilities (Hernández-Rodríguez et al., 2011; Pinna et al., 2018). Molecular techniques including conventional and real-time PCR offer higher sensitivity for detecting leptospiral DNA, particularly during early infection before seroconversion (Ahmed et al., 2009). While PCR typically shows optimal effectiveness with urine and renal tissues rather than serum due to the transient nature of leptospiremia, it remains valuable for epidemiological investigations (Stoddard et al., 2009; Subharat et al., 2011). Selection of diagnostic methods should align with specific research objectives, available resources, and infection stage (Musso et al., 2013).

This study analysed 902 retrospective cattle serum samples from 19 farms across PNG's Morobe Province. These samples were originally collected in 2017 through collaborative efforts by the National Agriculture Quarantine and Inspection Authority (NAQIA), then stored at -80°C at the PNG Institute of Medical Research (PNGIMR) facilities until 2022 when retrieved for quantitative real-time PCR analysis. This retrospective screening complements the current PhD research project on the "Incidence and Distribution of Leptospirosis in Cattle Population in the Morobe Province of PNG". Integrating historical data with current studies enhance understanding of regional leptospirosis dynamics, potentially revealing temporal patterns and ecological factors influencing transmission (Goarant 2016; Wynwood et al., 2014).

This study aimed to: (1) screen retrospective cattle serum samples for the presence of leptospirosis using qPCR; (2) establish the incidence and distribution of leptospirosis across different cattle farms in PNG's Morobe Province; and (3) generate reliable baseline information on leptospirosis to completement the current PhD research on disease epidemiology and control. Results will contribute significantly to developing targeted surveillance programs and preventive measures for leptospirosis in PNG livestock systems.

2. MATERIALS AND METHODS

2.1 Research Ethics

The retrospective samples were part of a previous collaborative project by NAQIA on animal disease surveillance that met all ethical requirements. As PNG's mandated biosecurity and animal health authority, NAQIA conducted sampling according to standard operating procedures.

2.2 Sampling Location

Cattle blood samples were collected in 2017 across commercial and smallholder farms throughout the Morobe Province. The study encompassed 19 cattle farms (Table 1), with access facilitated through prior coordination with NAQIA staff. Most farms were situated within the Markham Valley, with two exceptions: Ramu Agri Industry Limited, located in Gusap in the Ramu Valley, and Evangelical Brotherhood Church (EBC) and Pelgens farm, positioned 6 and 9 km outside of Lae City, respectively.

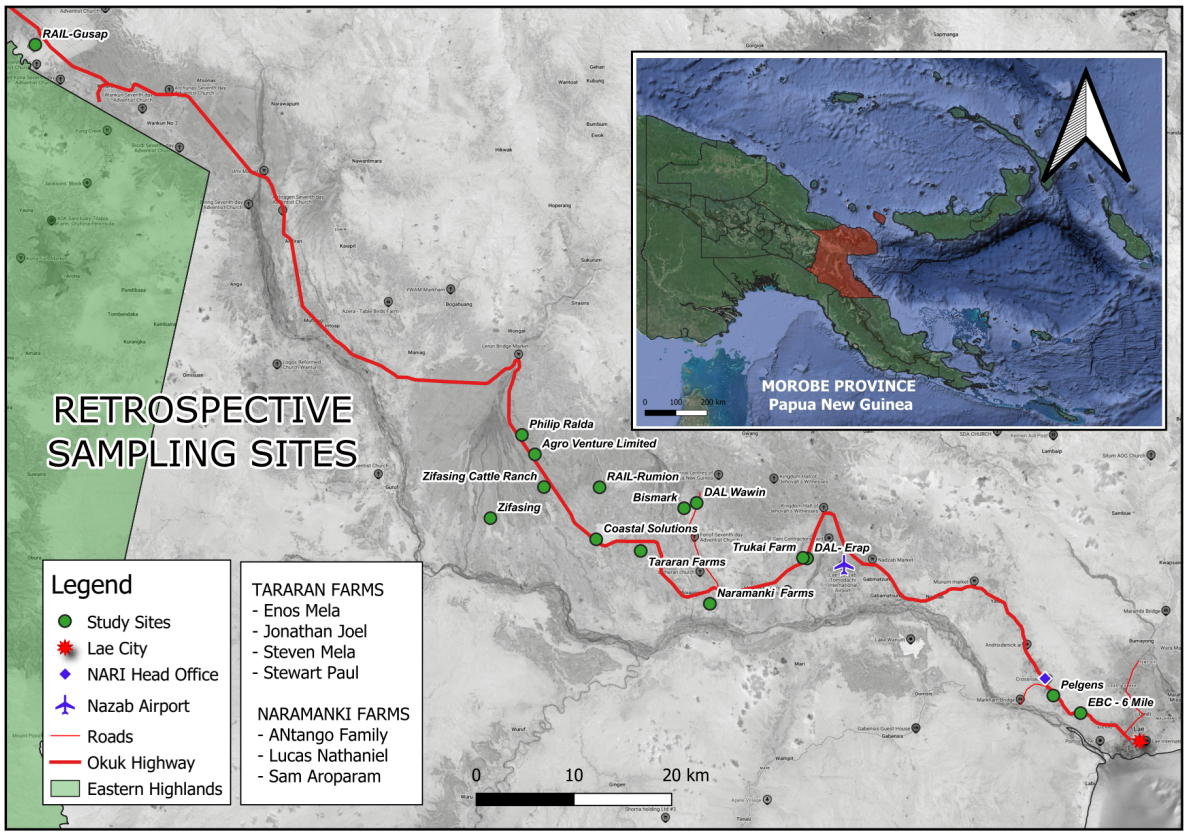

Figure 1. Geographical distribution of cattle serum sampling sites across Morobe Province, PNG. *(Map generated using QGIS software)*

Table 1. Name and locations of retrospective sampling sites.

#	Owner/Farm	Specific Location	Area
1	Antango Family	Naramanki	Markham Valley
2	Bismark	Warwin	Markham Valley
3	Coastal Solutions	Klin Wara	Markham Valley
4	DAL	Warwin	Markham Valley
5	DAL	Erap	Markham Valley
6	EBC	Six Mile/Lae	Lae City
7	Enos Mela	Tararan	Markham Valley
8	Jonathan Joel	Tararan	Markham Valley
9	Lucas Nathaniel	Naramanki	Markham Valley
10	Pelgens	Singawa/Lae	Lae City
11	Philip Ralda	Sasieng	Markham Valley
12	RAIL- Gusap	Gusap	Ramu Valley
13	RAIL Rumion	Rumion	Markham Valley
14	Sam Aroparam	Naramanki	Markham Valley
15	Steven Mela	Tararan	Markham Valley
16	Stewart Paul	Tararan	Markham Valley
17	Trukai Cattle Farm	Erap	Markham Valley
18	Zifasing	Zifasing	Markham Valley
19	Zifasing Cattle Ranch	Zifasing	Markham Valley

RAIL – Ramu Agri Industry Limited, DAL – Department of Agriculture and Livestock, EBC – Evangelical Brotherhood Church

2.3 Data Collection and Handling

NAQIA personnel, including veterinarians and certified animal health officers with specialized training in animal blood collection, obtained 902 blood samples from 19 cattle farms across the Morobe Province. Sampling was conducted randomly without regard to age or breed, with farm owners and workers helping with animal restraint when needed. Research personnel systematically documented environmental and operational characteristics at each site, recording secondary information such as farm type, cattle breed, and gender and age distribution of the herds.

Blood was aseptically collected from the jugular or tail vein of each animal using 10 ml syringes and 24-gauge butterfly needles, with approximately 4-5 ml drawn directly into red vacutainer tubes. Samples were maintained in an upright position in insulated containers with ice packs, preserving the cold chain during same-day transport to the nearby laboratory. After overnight storage at -4°C, samples were centrifuged at 3,000 rpm for 15 minutes to separate serum from whole blood. The separated serum was stored at -20°C until transportation. Upon completion of the field sampling, all serum specimens were repacked with ice packs and transported by road from Lae to the PNGIMR Goroka branch laboratory in the Eastern Highlands Province (a 5–6-hour journey), where they were immediately sorted and stored at -80°C until laboratory analysis. All subsequent procedures, including qPCR testing, were performed at PNG IMR research facilities.

2.4 DNA Extraction

DNA was aseptically extracted from each cattle serum sample, using the DNeasy Blood and Tissue Kit (Qiagen, Hilden, Germany) following the manufacturer's instructions conducted in a type A2 biosafety cabinet. One hundred microliters of each serum sample were used for the extraction. Purified DNA from each sample was equally aliquoted into 2 x 2 ml screw-cap tubes and stored at -80°C until required for qPCR testing.

2.5 Real-Time PCR Amplification and Detection of DNA

Extracted DNA samples were screened for *Leptospira* spp. using real-time PCR methodology as described by Smythe et al. (2002). The assay utilized specific oligonucleotides: forward primer (5′-CCC GCG TCC GAT TAG-3′), reverse primer (5′-TCC ATT GTG GCC GRA CA-3′), and a fluorogenic probe (5′-[FAM] CT CAC CAA GGC GAC GAT CGG TAG C[BHQ1]-3′). The qPCR master mix was prepared with nuclease-free water, Quantitech DNA master mix, forward and reverse primers (20 μM each), and probe (10 μM), with reagent volumes adjusted according to sample numbers per reaction. Amplification was performed using a CFX96 real-time PCR system (Bio-Rad, USA) with thermal cycling parameters consisting of initial activation at 95°C for 15 min, followed by 40 cycles of denaturation (94°C for 60 s) and annealing/extension (60°C for 90 s). *Leptospira* spp. detection was determined by amplification curves crossing threshold values (Ct-values) in real-time. All primers, probes, and positive controls were sourced from previous zoonotic disease studies conducted at PNGIMR (Javati et al., 2022; Robby et al., 2017).

2.6 Data Analysis

Primary data in this study were collected from field sampling and qPCR results. Information generated from qPCR was entered into Microsoft Excel 2021 spreadsheets (Microsoft, Redmond, USA) and analysed accordingly. The main variable for analysis was the presence of leptospirosis in each retrospective cattle serum sample across different farms. The presence (positive) or absence (negative) of leptospirosis was determined from the qPCR output. Additional survey information including geographical farm locations, number of samples collected from each farm, and cattle breed details are presented in graphs and tables. Graphical distribution of cattle samples, age, and gender across different farms was created using the ggplot package in RStudio.

2.7 Quality Management

Sample collection was conducted by qualified and experienced NAQIA personnel using appropriate standard operating procedures. Samples were stored under reliable and consistent temperatures to maintain freshness and quality over time. DNA quantification and measurement of impurities were performed using a spectrophotometer (Nanodrop) for quality assessment. Positive controls (*Leptospira* spp. from other studies) and negative controls (nuclease-free water) were included in all real-time PCRs runs to ensure reliability. Extracted DNA was stored in a -80°C freezer with consistent power supply to maintain temperature stability. The extracted DNA could be easily accessed and retested when required to ensure validation and reliability of the screening techniques.

3. RESULTS

Table 2. Real-time PCR results for leptospirosis screening in cattle serum collected from different farms in Morobe Province

Cattle Farm/Owner	Number of Samples	qPCR Ct Values	Results
Antango Family	34	0.00	Negative
Bismark	50	0.00	Negative
Coastal Solutions	63	0.00	Negative
DAL - Warwin	44	0.00	Negative
DAL – Erap	26	0.00	Negative
EBC	39	0.00	Negative
Enos Mela	50	0.00	Negative
Jonathan Joel	65	0.00	Negative
Lucas Nathaniel	31	0.00	Negative
Pelgens	56	0.00	Negative
Philip Ralda	63	0.00	Negative
RAIL -Gusap	60	0.00	Negative
RAIL Rumion	65	0.00	Negative
Sam Aroparam	24	0.00	Negative
Steven Mela	40	0.00	Negative
Stewart Paul	57	0.00	Negative
Trukai Cattle	68	0.00	Negative
Zifasing	41	0.00	Negative
Zifasing Cattle Ranch	25	0.00	Negative

**Positive control qPCR Ct value = 25.00 and Negative control qPCR Ct value = 0.00*

RAIL – Ramu Agri Industry Limited, DAL – Department of Agriculture and Livestock, EBC – Evangelical Brotherhood Church

The qPCR results indicated that 100% of retrospective cattle samples tested negative for *Leptospira* spp., showing no prevalence of leptospirosis in any of the cattle farms examined. DNA extracted from each blood serum sample was pooled in batches of five for qPCR analysis. The positive control yielded a threshold Ct value of 25.00, while the negative control had a Ct value of 0.00, confirming the validity of the real-time PCR runs and verifying that the results obtained for each farm were true negatives.

Table 3. Farm details comprising of farming system and distribution of cattle breed on each farm.

#	Cattle Farm/Owner	Farm Type	Cattle Breed
1	Antango Family	Small holder	Brahman
2	Bismark	Small holder	Brahman
3	Coastal Solutions	Large holder commercial	Brahman
4	DAL Warwin	Small holder	Brahman
5	DAL Erap	Small holder	Brahman

6	EBC	Small holder	Holstein
7	Enos Mela	Small holder	Brahman
8	Jonathan Joel	Small holder	Brahman
9	Lucas Nathaniel	Small holder	Brahman
10	Pelgens	Small holder	Brahman
11	Philip Ralda	Small holder	Brahman
12	Ramu Agri Industry Limited - Gusap	Large holder commercial	Brahman
13	Ramu Agri Industry Limited - Rumion	Large holder commercial	Brahman
14	Sam Aroparam	Small holder	Brahman
15	Steven Mela	Small holder	Brahman
16	Stewart Paul	Small holder	Brahman
17	Trukai Cattle Farm	Large holder commercial	Brahman
18	Zifasing	Small holder	Brahman
19	Zifasing Cattle Ranch	Small holder	Brahman

RAIL – Ramu Agri Industry Limited, DAL – Department of Agriculture and Livestock, EBC – Evangelical Brotherhood Church

Four farms, Ramu Agri Industry (Gusap and Rumion), Coastal Solutions, and Trukai cattle farms are large commercial holders while rest of the farms (n=15) are small holder based. The common cattle breed reared in all the farms are Brahman except in EBC farms where Holstein breeds are purposely raised for dairy (milk) production.

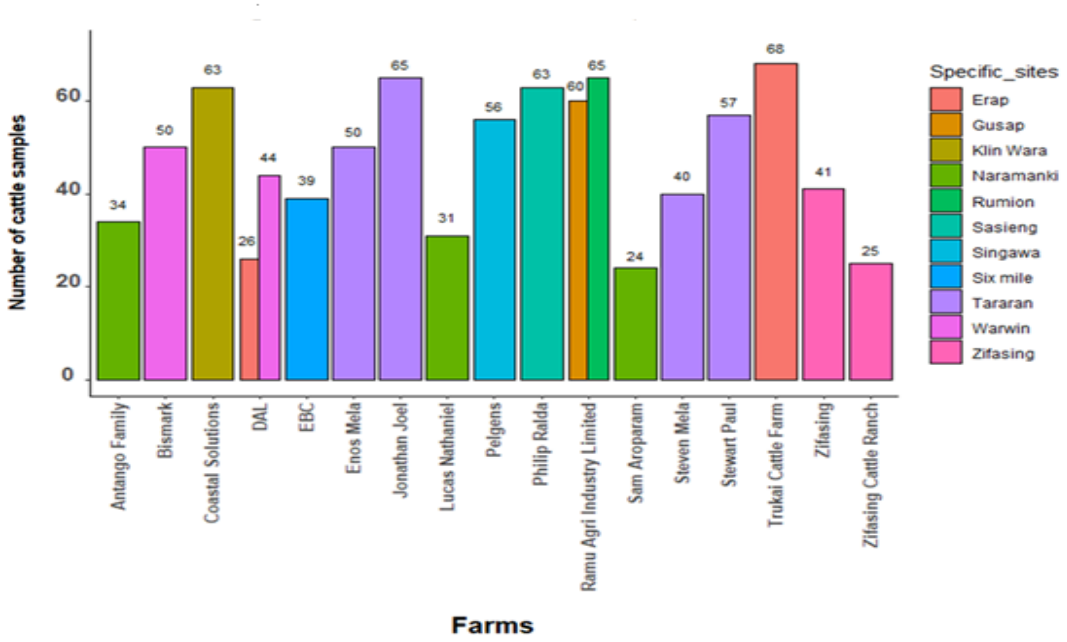

Figure 2. Distribution of cattle at each farm. *The figures on top of each bar plot show the number of cattle. For example, DAL farm is located at two sites; Erap and Warvin, however, the number of cattle sampled was higher in Warwin (n=44) than Erap (n=26).*

Several farms are located within specific sites. Farms owned by Antango Family, Lucas Nathaniel and Sam Aroparam are in Naramankib; Bismark and DAL in Warwin; Coastal Solutions in Klin Wara; DAL and Trukai Cattle Farm in Erap; EBC in Six Mile; Enos Mela, Jonathan John, Steven Mela and Stewart Paul in Tararan; Pelgens in Singawa; Philip Ralda in Sasieng; Ramu Agri Industry Limited in Gusap and Rumion; and Zifasing and Zifasing Cattle Ranch in Zifasing. Trukai Cattle Farm had the highest number of cattle samples (n=68) followed by Ramu Agri Industry Limited (n=65) and Jonathan Joel (n=65) with the least number found in Sam Aroparam farm (n=24). *Farm distribution and distance between farms are indicated in Fig. 2.*

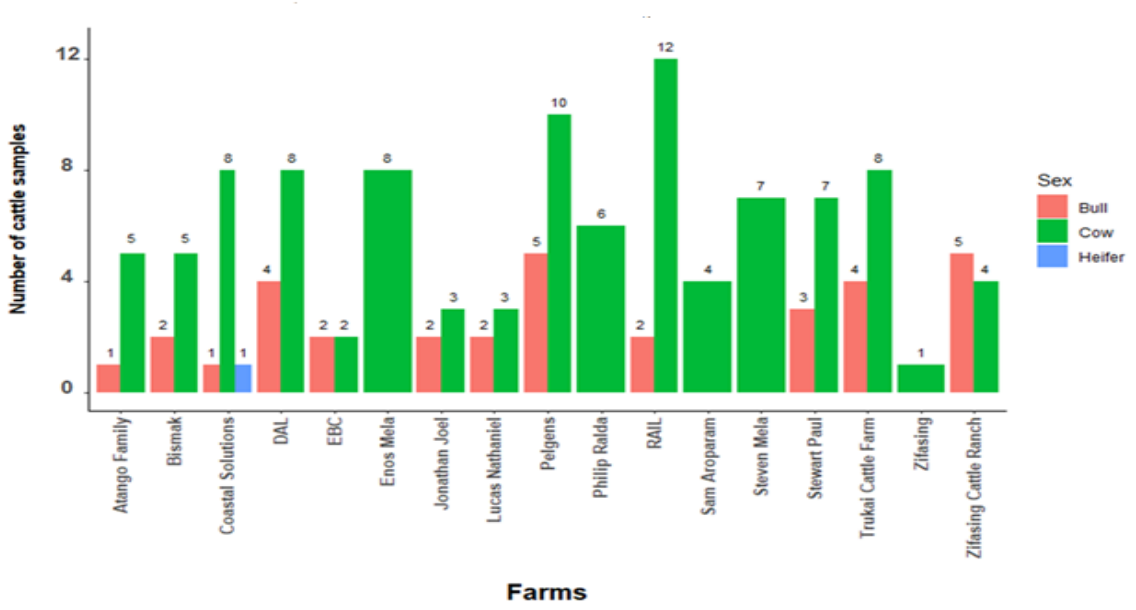

Figure 3. Distribution plot comparing the number of cattle at each farm and their sex or gender composition. *Some farms had both the male and female while others had only one gender. The figures on top of each bar plot shows the number of cattle.*

The sex and respective number of cattle samples varied across the farms. The number of samples corresponds to the size of farm and its status whether it is commercial or smallholder. The number of cows sampled was highest in Ramu Agri Industry Limited (RAIL) (n=12) followed by Pelgens (n=10) and lowest in Atango Family, Coastal Solutions and Zifasing (n=1) (Fig. 3). Only cows were sampled in Enoc Mela, Ralda, Sam Aroparam, Steven Mela and Zifasing. Both bulls and cows were sampled in Atango Family, Bismak, DAL, EBC, Jonathan Mela, Lucas Nathaniel, Pelgens, RAIL, Stewart Paul, Trukai Cattle Farm and Zifasing Cattle Ranch. All three age groups (bull, cow, heifer) were only sampled in Coastal Solutions.

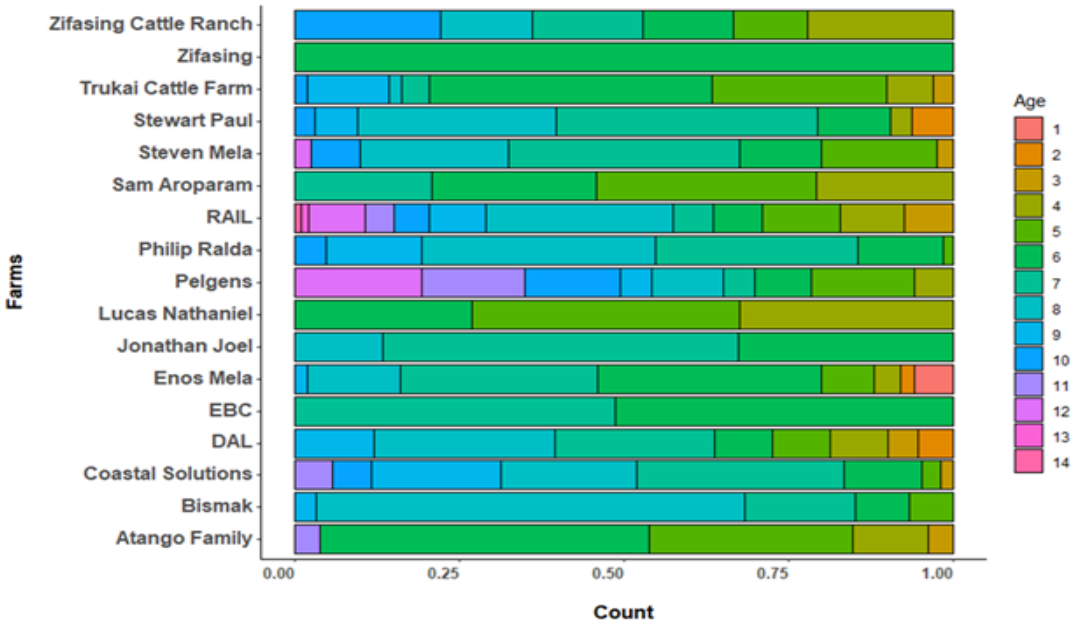

Figure 4. Age distribution of cattle across different farm. *To read the graph/figure for example: Atango Family farm had five age group which are 3, 4, 5, 6 and 11. Each age group contribution was 4%, 12%, 31%, 50% and 4%, respectively*

The distribution of age groups also varied across the farms (Fig. 4). We sampled the highest range of age groups at RAIL farm (n=12) with Age 8 being dominant (28%). The second highest range of age groups was sampled at Pelgens farm (n=9) with Age 12 being common (19%). In contrast, just two age groups, Age 6 and 7 were sampled at EBC farm respectively (51%, 49%) while a single age group (Age 8) was sampled at Zifasing farm (100%).

4. DISCUSSION

Retrospective screening for leptospirosis provides valuable understanding about past prevalence and distribution of the disease, enabling appropriate intervention and preventative measures (Garba et al., 2017). The screening of 902 retrospective serum samples from cattle populations in the Morobe Province revealed no positive results for leptospirosis through real-time PCR screening, despite employing a robust scientific approach and standard screening assay.

This non-detection, however, does not necessarily indicate the pathogen's complete absence in PNG's cattle population. Previous studies conducted within the Morobe Province have documented leptospirosis infection in cattle, confirming the presence of *Leptospira interorgan* serovar Hardjo and Tarassovi as dominant serovars (Wai'in 2007; Yombo 2006). These earlier investigations predominantly employed serological methodologies, specifically MAT and ELISA, for detection in blood and serum specimens. Notably, Yombo (2006) sero-epidemiological research revealed statistically significant variations in infection prevalence between agricultural establishments, with Markham Farm demonstrating a markedly higher incidence of active leptospirosis infection compared to Trukai Farm.

The absence of detectable leptospirosis may be partially attributed to vaccination status of the farms. Commercial farms and some smallholder operations may implement routine vaccination against endemic diseases, potentially reducing the likelihood of leptospirosis detection. Recent incursions of exotic animal diseases in PNG, such as African Swine Fever in pigs (PHARMAPlus 2021) and Newcastle Disease in poultry (Raitano 2010), may have enforced enhanced on-farm biosecurity measures and disease management strategies. However, information regarding vaccination and biosecurity protocols was unavailable for the sampled cattle farms. This limitation has prompted further investigation of presumed non-vaccinated cattle farms in subsequent chapters of this PhD project to better determine the true prevalence of leptospirosis in PNG.

4.1 Valuable Epidemiological Insights

Despite these limitations, our study yielded valuable epidemiological data regarding farm locations and cattle distribution patterns. Most cattle farms are centrally located along the Markham Valley, with some in proximity and others sharing land boundaries. This geographical clustering potentially facilitates disease transmission within or between farms. The Markham Valley's flat topography, high rainfall, and seasonal flooding create conditions favorable for leptospirosis transmission, as *Leptospira* spp. can survive up to 200 days under ideal environmental conditions (Pastre et al., 2020; Zelski 2007).

The study also revealed that 15 of the participating farms are smallholders, while four operate large-scale commercial enterprises. While farm management systems likely influence disease transmission, the retrospective data unfortunately did not provide sufficient information to evaluate management practices or disease control programs. Brahman cattle emerged as the dominant breed across all farms except EBC, which raises Holstein breeds primarily for dairy production. This breed preference is significant as Brahman cattle demonstrate better adaptation to tropical climates (Blackshaw et al., 1994; Hansen 2004), potentially affecting disease susceptibility patterns.

Cattle distribution varied considerably among farms, with nine operations (Bismarck, Coastal Solutions, Enos Mala, Jonathan Joel, Pelgens, Philip Ralda, Ramu Agri Industry Limited, Steward Paul, and Trukai) each providing 50 or more serum samples. Although the number of samples collected does not necessarily represent the total cattle population on each farm, densely populated operations generally face increased risk of disease transmission without proper management strategies. The study's analysis of gender and age distribution of cattle across farms further enhances the epidemiological value of this research, providing potential insights for

understanding how leptospirosis might distribute across different demographic groups, even though the pathogen was not detected in this study.

5. CONCLUSION

This retrospective investigation of cattle serum samples from the Morobe Province revealed no positive detections of *Leptospira* spp. through qPCR analysis, contrasting with previous documentation of *Leptospira interorgan* serovars in PNG cattle. This unexpected outcome may reflect prior vaccination practices in the sampled herds, though vaccination records were unavailable. Despite the absence of positive leptospirosis cases, the study generated valuable epidemiological data on farm distribution, cattle demographics, and environmental conditions potentially facilitating disease transmission. As part of our broader PhD research on leptospirosis in PNG livestock, these findings underscore the importance of investigating non-vaccinated farms in future studies. The discrepancy between our results and previous research warrants additional sampling to determine the true prevalence of leptospirosis in PNG cattle populations. The demographic data and sampling framework established through this investigation will inform ongoing epidemiological research and support the development of targeted surveillance strategies for this significant zoonotic disease, addressing both the economic impacts on livestock productivity and the associated public health concerns.

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Digital Health Transformation in Papua New Guinea

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Abstract: Papua New Guinea's healthcare system faces persistent challenges, including limited infrastructure, fragmented service delivery, and a predominantly paper-based system that hinders timely, effective care. This thesis paper investigates how digital technologies can transform healthcare delivery at Angau Provincial Hospital, one of PNG's key referral and teaching hospitals. Positioned within the broader context of national health priorities and UN's Sustainable Development Goals (SDGs 3, 9, and 17), the research study evaluates the hospital's readiness for digital health transformation and proposes phased, context-specific interventions to improve operational efficiency, patient safety, and healthcare accessibility. Using a qualitative case study methodology, supported by stakeholder analysis and comparative insights from international implementations, including Kenya's mobile health platforms, India's hospital information systems, and Port Moresby General Hospital's early telehealth adoption, the research identifies practical pathways for integrating electronic health records (EHRs), digital inventory systems, and telemedicine at Angau. In addition, comparative international case studies from India, Kenya, Estonia, and Rwanda underscore the feasibility and benefits of digital health interventions in resource-constrained settings. It also outlines strategies for overcoming PNG-specific constraints such as poor internet connectivity, low digital literacy, and limited funding. The study finds that with targeted investment in infrastructure, capacity-building, and collaborative partnerships with stakeholders such as UNDP, WHO, and DFAT, Angau can become a national model for digital health transformation. The thesis paper concludes with a roadmap for implementation and highlights future research needs in digital infrastructure scaling, policy development, and workforce training. This research contributes to the growing discourse on digital equity and health system modernization in low-resource settings, offering Angau and PNG a clear vision for inclusive, technology-enabled healthcare.

Keywords: Angau, Digital health transformation, healthcare, health information systems, Papua New Guinea (PNG).

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1. INTRODUCTION

Healthcare systems worldwide are evolving rapidly, fueled by the integration of digital technology. The use of digital tools such as electronic health records (EHRs), telemedicine platforms, mobile health (mHealth) applications, and health information systems (HIS) has revolutionized service delivery in many countries, improving access, enhancing patient safety, and enabling real-time data-driven decisions (WHO, 2020). In high-income countries, such technologies have become central to patient care and hospital management, yet low- and middle-income countries (LMICs), including PNG, face significant barriers to implementation.

PNG's healthcare system is under severe pressure. Challenges such as inadequate infrastructure, poor road networks, chronic shortages of skilled personnel, lack of reliable power and internet connectivity, and limited public health funding severely restrict the quality and reach of healthcare services (World Bank, 2024; WHO, 2021). The COVID-19 pandemic further exposed the system's fragility and highlighted the urgent need for scalable, resilient healthcare solutions ((UNDP, 2023), PNGIMR, 2022; Vallely, 2024).

Moreover, Papua New Guinea (PNG) faces significant challenges in its healthcare system, including limited infrastructure, a shortage of skilled health professionals, and geographic barriers that hinder access to essential services. The World Health Organization (2023) recommends a ratio of one doctor per 1,000

people, but PNG currently has approximately 640 doctors, resulting in a ratio of one doctor per 20,000 people (ICT.gov.pg, 2025).

In response to these challenges, PNG has initiated a national digital health strategy aimed at transforming its healthcare system through the integration of Information and Communication Technology (ICT). This strategy includes the development of an ICT policy, a digital health toolkit, and a comprehensive digital health roadmap to guide the implementation of ICT solutions in the health sector (World Bank, 2025).

Digital health interventions, such as mobile health applications, electronic health records, and telemedicine, offer promising solutions to improve healthcare delivery in remote and underserved areas. For instance, mobile technologies and geographic information systems have been utilized to enhance health information systems in PNG, facilitating better data management and decision-making (Rosewell, 2021).

The Angau Hospital entirely reliant on paper-based processes leads to delays in patient care, duplication of services, and data loss. In rural areas, where access to specialist care is limited, telehealth could expand access and improve patient outcomes. Integrating digital health into Angau's operations is not only feasible but necessary to modernize its service delivery and align with national and global health objectives. Digital transformation presents a unique opportunity to address these systemic issues. For instance, EHR systems can help reduce medical errors and improve continuity of care, while mobile technologies can extend healthcare access to rural and remote communities. Moreover, telemedicine has proven particularly effective in areas with few specialists, as evidenced by initiatives in Kenya, India, and Indonesia, where similar socioeconomic challenges have been mitigated through digital health innovations (WHO, 2020).

The United Nations Sustainable Development Goals (SDGs) further underscore the relevance of digital health. Specifically, SDG 3 aims to ensure healthy lives and promote well-being for all at all ages (UN, 2015), while SDG 9 promotes innovation and sustainable infrastructure (United Nations, 2015) and SDG 17 calls for international cooperation to achieve development outcomes (UN, 2015). Papua New Guinea's Vision 2050 and National Health Plan 2021–2030 echo these priorities, emphasizing universal health coverage, equity in service delivery, and strengthened governance through ICT (Department of National Planning & Monitoring, 2020; Department of Health, 2020).

Angau Hospital, one of PNG's largest public healthcare institutions, serves as an ideal case study to explore these transformative opportunities. The hospital's infrastructure investments under the PNG-Australia Partnership have created a baseline for integrating digital health systems. However, to fully leverage these advancements, targeted digital strategies are necessary to overcome persistent operational challenges and improve healthcare delivery.

This research examines how digital health tools can be effectively integrated into Angau's operations to enhance clinical outcomes, streamline administration, and support health system strengthening. By analyzing local context, stakeholder readiness, and international case studies, the research seeks to provide practical, cost-effective, and sustainable digital health solutions for PNG.

2. LITERATURE REVIEW

The World Health Organization emphasizes the potential of digital health to address pressing global challenges through innovations such as mHealth applications, telemedicine, and data analytics (WHO, 2021; UNDP, 2023). Telehealth has been shown to overcome geographical barriers and improve healthcare access in resource-constrained settings (Scott & Mars, 2015). Similarly, successful adoption of ICT in healthcare depends on enabling factors such as strong leadership, staff training, and reliable infrastructure (Gagnon et al., 2016).

In the Pacific Islands, including Papua New Guinea, adoption of digital health has been limited. However, pilot initiatives show promise when designed to align with cultural contexts and logistical realities (MacLaren et al., 2020). These findings suggest that while barriers remain, digital health tools can be transformative when adapted to local needs and supported by effective policy frameworks.

2.1. Global Context of Digital Health Transformation

In Kenya, the use of the AMREF Health Africa telemedicine platform has facilitated remote diagnosis and specialist consultations in hard-to-reach rural clinics (Kamau, 2021). The program has reduced patient travel time and improved access to maternal and child health services, demonstrating cost-efficiency and scalability (AMREF, 2020). Kenya's M-TIBA platform allowed users to save and manage health funds through mobile phones, improving transparency and access to care (Kamau, 2021). The system strengthened health financing and accountability.

Similarly, India's eSanjeevani initiative, launched by the Ministry of Health and Family Welfare, provided over 30 million teleconsultations by 2022, significantly expanding healthcare access during the COVID-19 pandemic (MOHFW, 2021).

In Indonesia, the Puskesmas model, community-based primary health centers has integrated digital platforms to monitor patient data and manage referrals, resulting in improved care coordination and faster patient throughput (PATH, 2025; Ministry of Health Indonesia, 2024)."These global examples offer practical insights into how Angau Provincial Hospital might integrate digital solutions despite infrastructural and budgetary limitations.

Estonia's health system is often highlighted for its advanced digital transformation. By 2020, over 99% of prescriptions and health records were digitized. This resulted in reduced administrative costs, faster service delivery, and improved chronic disease management ((Aaviksoo et al., 2020).

India's eSanjeevani, a government-led telemedicine service, conducted over 50 million consultations during the COVID-19 pandemic, especially in underserved rural areas (MOHFW, 2021). The platform demonstrated the power of low-cost, scalable digital infrastructure in a resource-constrained setting.

Rwanda's national eHealth strategy emphasized maternal health monitoring and digital health worker training. In five years, maternal mortality rates dropped by 60%, attributed to improved digital referral systems and real-time data management (WHO, 2020).

Bangladesh implemented a national Health Information System with EHRs at the primary healthcare level. Despite infrastructure constraints, the initiative improved immunization tracking and rural health monitoring (Islam, 2018)

Brazil's Telessaúde Brasil Redes expanded telemedicine services to remote Amazonian regions, enhancing specialist access and professional development among rural health workers (Giovanella, 2019).

Fiji adopted the DHIS2 platform for real-time data reporting. Supported by WHO and international donors, the system improved vaccination coverage and disease surveillance across islands (WHO Pacific Office, 2020).

These cases demonstrate that low- and middle-income countries can successfully implement digital health technologies by leveraging partnerships, open-source platforms, and strong policy frameworks.

2.2. PNG's Digital Health Landscape

PNG's 2023 Digital Health Strategy identified several barriers: poor ICT infrastructure, limited digital literacy, and lack of system interoperability (UNDP, 2023). However, the strategy outlines opportunities for progress through donor partnerships, mobile phone penetration, and alignment with national health plans. The Angau Provincial Hospital case study is crucial in testing and scaling these opportunities.

2.2.1. PNG's Digital Health Landscape: The Case Study of Port Moresby General Hospital

Port Moresby General Hospital (PMGH), is the largest referral hospital in Papua New Guinea, has taken early steps toward adopting digital health practices, making it a relevant comparator for Angau. PMGH's experience illustrates the gradual shift from paper-based to semi-digital systems in PNG's public health sector. For example, PMGH has implemented a pilot Electronic Medical Record (EMR) system within selected departments such as outpatient, radiology, and laboratory services. According to a report, the Electronic Medical Record (EMR) system in Papua New Guinea has improved data accuracy, reduced patient wait times, and facilitated better

coordination between clinicians (PNG NDoH, 2021). Moreover, PMGH has collaborated with international partners including WHO and DFAT to integrate digital reporting for infectious diseases. This has enabled real-time surveillance of COVID-19 cases and enhanced national coordination of pandemic responses.

Additionally, the hospital has started using mobile health apps to send reminders to patients about follow-up appointments and medication schedules, thereby improving patient compliance and reducing hospital readmissions (PNG NDoH, 2022).

Despite these gains, challenges persist. The rollout of digital systems at PMGH has been hindered by inadequate training for staff, irregular power supply, and limited IT support. Nonetheless, PMGH's partial digitization serves as an instructive model for Angau, highlighting both opportunities and pitfalls in implementing digital health strategies in the PNG context. Lessons from PMGH suggest that strong leadership commitment, external funding, and phased implementation are essential to success (PNG NDoH, 2022).

2.2.2 Case Study: Angau Provincial Hospital

Angau Provincial Hospital exemplifies many of the systemic challenges facing PNG's healthcare system. As one of only four regional referral hospitals in the country, Angau serves as the primary medical facility for the northern half of PNG. With an estimated patient volume of over 70,000 outpatient visits per year, the hospital's infrastructure is under significant strain (PNG NDoH, 2022).

Currently, all patient records are maintained manually. Paper files are susceptible to misplacement, duplication, and delayed retrieval, leading to diagnostic errors and inefficient patient flow. Staff rely on handwritten notes, which are often illegible, especially in emergency care. There is no centralised patient database or referral tracking system, making continuity of care difficult when patients are referred between departments or other provincial clinics.

The hospital's pharmacy department also operates on a paper-based inventory system, contributing to frequent medicine stock-outs and wastage from expired drugs. Without digital inventory management, tracking/monitoring procurement, usage trends, or urgent supply needs is nearly impossible. Similarly, laboratory and radiology departments suffer from long processing times and miscommunications due to the lack of integrated information systems.

In addition, field data collected from Angau revealed several systemic inefficiencies. Over 90% of patient records are paper-based, leading to frequent data loss and duplication. Referrals are poorly coordinated, resulting in delayed treatments. Supply chain management is manual, contributing to stock-outs. Staff expressed interest in digital solutions but cited lack of training and support.

The hospital could adopt a phased approach to digital health. Phase 1 could introduce EHRs in outpatient services using open-source platforms like OpenMRS. Phase 2 might involve inventory digitization and staff training. Phase 3 would launch telemedicine services targeting rural outreach. These interventions align with national goals and donor priorities.

Furthermore, efforts to pilot basic health data collection through mobile tablets provided under the Australian Government's support program were launched in 2021 but have not yet scaled due to inadequate staff training and poor internet connectivity (DFAT, 2022). Staff enthusiasm for digital solutions exists, but the lack of an institutional roadmap has resulted in fragmented attempts at digitization.

Despite these barriers, Angau's situation also presents an opportunity. A structured digital implementation plan, starting with a robust hospital information system (HIS), digital appointment scheduling, and e-prescriptions, could significantly improve efficiency and reduce the workload on frontline staff. The hospital could also implement a basic cloud-based EHR system, accessible to departments and affiliated clinics, to streamline referrals and follow-ups. Additionally, telemedicine pilot programs could link Angau with Port Moresby General Hospital or even international experts for complex cases. Such collaborations would enhance diagnostic accuracy, improve staff training through virtual learning, and reduce the need for expensive patient travel.

In summary, Angau's challenges reflect the broader state of healthcare in PNG, but they also highlight the transformative potential of targeted digital interventions. With phased investments, donor partnerships, and a focus on capacity building, Angau Provincial Hospital can evolve into a flagship for digital health transformation in PNG.

3. OBJECTIVES OF THE STUDY

1. To assess the current healthcare delivery challenges at Angau Provincial Hospital.
2. To explore suitable digital health technologies applicable to PNG.
3. To compare global best practices and case studies for relevance.
4. To recommend implementation strategies aligning with PNG's development goals and Sustainable Development Goals (SDGs).

4. METHODOLOGY

4.1 Research Design

A qualitative case study design was selected to provide an in-depth understanding of healthcare delivery challenges and digital transformation prospects at Angau Provincial Hospital.

4.2 Data Sources

Primary data were obtained through stakeholder interviews. While Secondary data were sourced from health policy documents, project evaluations, academic literature, hospital reports, and peer-reviewed literature.

4.3 Case Study Method

The case study method facilitated contextual analysis of challenges and potential digital solutions specific to Angau Provincial Hospital.

4.4 Data Analysis

Data were coded and analyzed thematically to identify recurring patterns in service delivery issues, stakeholder perceptions, and proposed digital interventions.

5. RESULTS / FINDINGS

- Staff frequently lose patient records due to manual filing.
- Referral delays are common due to lack of a centralized communication system.
- Mobile device usage among staff is high, indicating potential for mHealth.
- Staff lack digital skills but are open to training.
- Donor interest in digital pilots is evident, particularly from DFAT and WHO.

To evaluate the feasibility and readiness of Angau Provincial Hospital for digital transformation, data were collected from hospital reports, staff interviews, observational studies, and comparisons with national and international benchmarks. The table below presents key findings:

Table 1. Digital Transformation at Angau Provincial Hospital

Category	Angau Provincial Hospital (Current)	Benchmark/global comparison	Key Observations
Patient Record System	100% manual (paper-based)	70-90% digital in middle-income countries (e.g., India, South Africa)	Delays in retrieving records; risk of data loss.
Internet Connectivity	Intermittent; <1 Mbps average speed	10-50 Mbps in digital hospitals	Inadequate for real-time telehealth or cloud-based systems.
Staff Digital Literacy	~35% staff trained in basic IT usage	>85% in ICT-enabled hospitals	Training gap identified as critical barriers to adoption
ICT Infrastructure	Limited to administrative office and a few computers	Centralized HER servers, department-level devices	Lack of department-specific ICT systems
Power Reliability	Daily outages lasting up to 2-4 hours	<1 hour/month (backup systems in place)	Unreliable power hinders system uptime and data security.
Pharmacy Stock Tracking	Manual inventory logs, updated weekly	Real-time digital dashboards (e.g., Kenya's mSupply)	Prone to errors and stock-outs.
Telemedicine Access	None	Integrated video consultations in remote areas	High potential for implementation using mobile networks.
Data Reporting to NDoH	Monthly paper reports	Automated digital dashboards in many global systems	Reporting delays impact national planning and funding.
Stakeholder Readiness	High enthusiasm; low technical preparedness	Full integration teams in global case studies	Support available, but requires capacity-building.
SDG Alignment	Partial (aligned to SDG 3, but limited in practice)	Strategic alignment with SDG 3,9, and 17 in eHealth	Opportunities to align with international donors and frameworks.

These findings clearly show both the current gaps and the opportunities for digital transformation at Angau. The data suggests that with targeted infrastructure investments, capacity building, and strategic partnerships, the hospital can align with regional and global best practices in digital health.

6. DISCUSSION

Digital transformation is both timely and necessary for Angau Provincial Hospital. EHRs can reduce medical errors and improve data management. Mobile-based inventory systems can prevent stock-outs. Telemedicine could connect Lae-based doctors with remote patients. Lessons from Estonia, India, Rwanda, and Kenya demonstrate that resource-constrained settings can benefit from digital health when supported by proper planning, capacity building, and stakeholder engagement. A key success factor is leadership commitment and sustained funding. .

Furthermore, the results also demonstrate a critical need for digital transformation at Angau Provincial Hospital. Manual processes, lack of coordination, and inadequate record management undermine patient care and institutional efficiency. Similar to the international examples reviewed, implementing digital tools like EHRs and telemedicine can yield significant improvements in patient safety, timeliness of care, and staff productivity.

The hospital's current operational model fails to adequately serve a growing population. Yet the staff's openness to innovation and the presence of donor support indicate a readiness for change. The evidence from

India and Rwanda shows that even modest investments in mobile health and referral systems can dramatically reduce maternal mortality and improve access to care. The success of Estonia and Brazil in adopting digital solutions across the care continuum offers a scalable blueprint for Angau's transition. Another key insight is the role of partnerships and government alignment. The SDGs and PNG's national health policy both emphasize collaboration and technological innovation. Aligning Angau's digital strategy with these frameworks will enhance its ability to secure funding, training, and technical expertise from agencies like WHO, UNDP, and DFAT.

The discussion also highlights the importance of leadership and institutional culture. Digital transformation requires champions who can build consensus, manage change, and ensure accountability. Investment in capacity building, both technical and managerial, is crucial for sustaining digital health gains. The creation of a Digital Health Taskforce at Angau, comprising hospital administrators, clinicians, Information Communication and Technology (ICT) professionals, and donor representatives, could help coordinate implementation and monitor progress. Finally, the importance of a phased approach cannot be overstated. Starting with outpatient EHRs, followed by supply chain digitization, and culminating in a telemedicine rollout ensures manageable change, minimizes risk, and provides opportunities to refine systems before scaling.

7. RECOMMENDATIONS

1. Implement open-source EHRs starting in outpatient departments.
2. Partner with universities and NGOs for ICT training.
3. Pilot mobile health tools for community health workers.
4. Upgrade internet and hardware infrastructure with donor support.
5. Integrate digital health into national policies and hospital development plans.
6. Create a monitoring framework to evaluate digital health performance.

In addition, to improve, adopt, and implement new digital technologies despite challenges like poor internet connectivity, **Angau Provincial Hospital** can follow a **phased, adaptive, and context-specific strategy** that includes the following key components:

7.1. Conduct a Digital Readiness Assessment

- **Evaluate current infrastructure**, staff digital literacy, electricity reliability, and internet access.
- Identify **departments with the highest need** for digitization (e.g., patient records, pharmacy, and outpatient).

7.2. Adopt Hybrid Digital Systems

- Use **offline-first software** that syncs data when internet is available (e.g., CommCare, DHIS2).
- Deploy **local servers** for storing patient data, with regular backups to cloud systems when connectivity allows.

7.3. Improve Internet Access Strategically

- Partner with local telecom companies to install **dedicated VSAT (satellite internet)** or 4G hotspots in critical hospital departments.
- Use **mesh Wi-Fi networks** to extend coverage from a central hub to multiple buildings.
- Apply for **government or donor-supported connectivity initiatives**, such as those supported by DFAT or WHO.

7.4. Implement in Phases

- **Phase 1**: Digitize the patient registration and outpatient record system using tablets and local servers.
- **Phase 2**: Add pharmacy stock management, lab requests, and appointment scheduling.
- **Phase 3**: Expand to telemedicine and integrate with national health systems.

7.5. Build Capacity and Train Staff

- Conduct regular **digital literacy training** for clinical and admin staff.
- Appoint **digital champions** in each department to support adoption and troubleshooting.
- Collaborate with **universities or NGOs** to provide eHealth training modules.

7.6. Monitor and Evaluate Progress

- Create KPIs (e.g., patient wait times, stock-outs, record accuracy).
- Use simple **dashboards** to track data even without real-time internet.
- Adjust implementation plans based on feedback and periodic evaluation.

7.7. Collaborate and Seek Funding

- Align projects with **Sustainable Development Goals (SDG 3 and 9)** to attract support.
- Submit proposals to **UNDP, WHO, DFAT**, and **Asia-Pacific digital health donors** for infrastructure, training, and software support.

By combining local innovation, phased implementation, offline-capable technology, and partnerships, Angau can begin its digital health transformation even with limited connectivity.

8. CONCLUSIONS

In conclusion, digital health tools can significantly enhance healthcare delivery at Angau Hospital. By starting small and scaling sustainably, the hospital can serve as a model for nationwide implementation. Future studies should focus on patient experiences, cost-benefit analyses, and long-term health outcomes. This study has examined the critical role of digital technology in enhancing healthcare delivery at Angau and, by extension, across PNG's broader health system. The case study underscores that, despite significant structural and systemic challenges, including outdated infrastructure, poor internet connectivity, and limited digital literacy, there is enormous potential for transformation through the strategic implementation of cost-effective and context-specific digital health solutions. The hospital currently relies on manual, paper-based systems that compromise efficiency, patient safety, and service quality. However, global best practices and comparative studies, including examples from Kenya, India, and Australia's own telehealth outreach programs, demonstrate that with the right approach, even resource-constrained environments can successfully adopt and benefit from digital transformation.

Notably, PMGH has taken preliminary steps toward eHealth integration, offering a useful national model. Through phased digitization of health records, pharmacy inventories, scheduling, and telemedicine, Angau can significantly improve patient outcomes, operational efficiency, and clinical accuracy. Critical to this success will be investments in digital infrastructure, staff training, policy support, and collaboration with national and international stakeholders. This transformation must also align with Sustainable Development Goals (SDGs) 3 (Good Health and Well-being), 9 (Industry, Innovation and Infrastructure), and 17 (Partnerships for the Goals). In conclusion, Angau stands at a pivotal moment. With thoughtful planning, stakeholder commitment, and adaptive technologies, it can become a national leader in digital health, setting a benchmark for improving healthcare delivery across PNG. This transformation not only supports national health priorities but also contributes meaningfully to the global digital health movement.

In addition, while challenges such as infrastructure, funding, and workforce capacity persist, digital health technologies offer transformative potential for Angau and beyond. With political will, community involvement, and coordinated donor support, Angau can be positioned as a beacon of innovation within PNG's health sector. Strong leadership and ongoing evaluation will be essential in navigating this digital shift. To maximize the impact of digital technologies, it is imperative that Angau adopts a holistic digital health transformation roadmap. This should include comprehensive policy development, stakeholder engagement at all levels, investment in ICT infrastructure, and integration with national health and education systems. This multi-sectoral collaboration can enable a digitally empowered health ecosystem that supports equitable and quality healthcare delivery for all Papua New Guinean.

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Causes and Effects of Climate Variability in the Pacific Island of Papua New Guinea

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Abstract: The pacific island of Papua New Guinea is the third largest rainforest in the world. The forests help maintain the agricultural land and protect people and crops from floods and landslides. From year 2001 to 2023, there is a tree cover loss of 0.89% mainly due to deforestation and a small percentage of forest fire. This results in about five million tons of carbon dioxide emission per annum. An analysis has been done to study the spacial and temporal changes in the climate of Papua New Guinea using published meteorological parameters for a period 2001-2020. Dry and wet conditions in different regions of Papua New Guinea in different years were identified by calculating Rainfall Anomaly Index. It is observed that dry conditions prevail in some regions of the country due to warming of the atmosphere. Also, El Nina/La Nina events and deforestation influenced the climate to some extent.

Key words: Atmospheric temperature, rainfall, El Nino, La Nina, trend, rainfall anomaly index

1. INTRODUCTION

Global atmospheric temperature is increasing steadily and the projected rise in temperature will be 2^0 by 2100 (Yun Gao et al., 2017). Global surface temperature changed as doubling of atmospheric Carbon dioxide levels (Cubasch et al., 2001). Studies on extreme temperature events showed the importance climate change impacts (Hegerl et al., 2004; Tebald et al., 2006). Changes in photosynthesis and evapotranspiration are more affected by T_{max} and T_{min} (Dhakhwa and Camphbell, 1998). Like any other country, Papua New Guinea is vulnerable to climate change. It will affect agriculture, financial resources and many other factors. Farmers face a significant challenge. The change in rainfall has direct impact on farm productivity.

Climate variations in four regions; Port Moresby, Goroka, Nadzab and Kavieng, of Papua New Guinea, which have unique climate, were analyzed in this study. This study helps to increase our understanding of climate pattern and weather and provides insights into how these patterns change over time. Port Moresby is the capital city of Papua New Guinea which experiences tropical climate characterized by high temperature, high humidity and wet and dry seasons. Wet season is from November to April characterized by rain and thunder storms and dry season is sunny with less precipitation. Goroka is located in the Eastern Highlands Province which is known for its rugged terrains and landscapes. The elevation is about 1600 meters surrounded by steep mountains and deep valleys. The climate in Goroka is generally cool and temperate with average temperature ranging from 10-25^0C throughout the year. Coffee and tea plantations are the main crops grown in the area. Nadzab is a place in Lae which is located on the northern coast of PNG main land. The Bismarck Sea is in the north and the rain forest covered mountains are in the south. The climate is tropical with high temperature and humidity throughout the year. The region's weather is influenced by the South Pacific Convergence Zone (Kazuyo et al., 2014). Kavieng is situated on the western coast of an island New Ireland in Pacific Ocean which is a part of PNG. The climate of Kavieng is tropical with high humidity. The place is filled with green rainforests, beaches and coral reefs. The terrain is mountainous and the mountains are covered with rainforests and are home to a diverse range of flora and fauna. The wet season lasts from December to March with heavy rainfall and tropical cyclones. The dry season is from May to

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October with less rainfall and lower temperatures. The rainfall variability is very much related with El Nino and La Nina events (Ian et al., 2013).

It is important to study T_{max} and T_{min} separately when assessing climate change impact (David et al., 2007). The spatial and temporal changes in atmospheric temperature and rainfall are analyzed to study climate change in Papua New Guinea. By studying the localized variation, we can develop strategies to mitigate its impact. In this study, we analyzed the daily maximum temperature (T_{max}) and daily minimum temperature (T_{min}) and rainfall from 2001 to 2020 in four regions of Papua New Guinea. We also analyzed the forest loss and green loss in these regions in the same period. The variation of rainfall during El Nino-La Nina events were also studied. This study is useful in developing strategies for mitigation and build resilience against extreme climate events.

1.1 Data Analysis

The data used in the study are the monthly average values of maximum and minimum values of the atmospheric temperatures and the monthly rainfall data measured in various centers namely POM, Goroka, Nadzab and Kavieng for the period from 2001 to 2020 published by Meteorological Department, Papua New Guinea. The forest loss data is taken from PNG Conservation and Environment Protection Agency (https://www.globalforestwatch.org). The SST and SOI data are taken from NASA website. (https://www.ncei.noaa.gov).

1.2 Trend Analysis

Significant trend of a time series can be found out by either parametric or non-parametric methods. If the data is independent and normally distributed, parametric method is used whereas if the data is only independent, non-parametric method is used (Gocic and Trejkovic, 2013). In this analysis, we used Mann-Kendall and Sen's slope estimator which are non-parametric in nature. Mann-Kendall test is used to determine the sense of the trend whether it is increasing or decreasing whereas Sen's slope estimator is used to determine the magnitude of the trend.

The Mann- Kendall statistics is given by

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad (1)$$

where x_i and x_j are the data values in the time series I and j respectively and n is the total number of data points.

$$sgn(x_j - x_i) = \begin{cases} +1 \; if \; x_j > x_i \\ 0 \; if \; x_j = x_i \\ -1 \; if \; x_j < x_i \end{cases} \quad (2)$$

If the number of observations is more than 10, Mann-Kendall statistic follows normal distribution with variance σ^2 given by

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \quad (3)$$

Z test is used to test the significance of the trend. The standard Z statistic is given by

$$Z_s = \begin{cases} \frac{S-1}{\sigma} \; if \; S > 0 \\ 0 \quad if \; S = 0 \\ \frac{S+1}{\sigma} \; if \; S < 0 \end{cases} \quad (4)$$

If $Z_s > Z_{table}$, the null hypothesis is rejected or a significant trend exists.

To determine the magnitude of the trend, Sen's slope estimator is used. The amount of change in parameter per unit time Q is given by

$$Q = \frac{X_j - X_k}{j-k}, k \neq j \quad (5)$$

For the time series data X of n values, N = n(n-1)/2 values of Q can be calculated. The Sen's slope estimator Q^* is the median of the N values of Q.

$$Q^* = \begin{cases} Q_{(N+1)/2} & if\ N\ is\ odd \\ \frac{Q_{(N/2)} + Q_{(N+2)/2}}{2} & if\ N\ is\ even \end{cases} \quad (6)$$

The numerical value of Q^* gives the degree of steepness of the trend.

1.3 Rainfall Anomaly Index

RAI is used to determine the anomaly in rainfall in a year whether it is positive or negative (Van-Rooy, 1965). To calculate RAI, the yearly rainfall data is arranged in the descending order and the average of the ten highest values is taken as the positive threshold value and the average of the ten lowest values is taken as the negative threshold value. The positive and negative threshold values are assigned +3 and -3 respectively. The positive and negative anomaly values are classified into six classes ranging from extremely wet to extremely dry conditions. Positive values are classified by wet conditions and negative values are classified by dry conditions.

$$RAI = 3\left(\frac{RNF - RNF_m}{X - RNF_m}\right) \quad for\ Positive\ anomaly \quad (7)$$

$$RAI = -3\left(\frac{RNF - RNF_m}{Y - RNF_m}\right) \quad for\ Negative\ anomaly \quad (8)$$

where RNF = current yearly rainfall (mm), RNF_m = average of the yearly rainfall for the period of study, X = the positive threshold value of rainfall and Y = the negative threshold value of the rainfall.

2. RESULTS AND DISCUSSION

The trend of variation of atmospheric temperature is determined by Mann-Kendall statistics and Sen's slope indicator. The yearly average values of T_{max} and T_{min} are calculated and the Z values of Mann-Kendall and Sen's slope indicators are calculated using the relations (1)-(6). Table 1 gives the Z values of Mann-Kendall and Sen's slope indicators of T_{max} and T_{min} in PNG and also in the four regions POM, Goroka, Kavieng and Nadzab. In PNG, a significant positive trend is observed in both maximum and minimum temperatures of the atmosphere. An increase in trend of 0.02^0 C per year is observed in maximum temperature whereas an increase in temperature of 0.015^0 C per year is observed in minimum temperature. If we observe the trend of variation in POM, Goroka, Kavieng and Nadzab, a significant increasing trend of T_{max} is observed in POM with an increase of 0.013^0 C per year. A significant increase in trend of T_{min} is observed in Goroka and Kavieng with an increase of 0.016^0 C and 0.023^0 C per year respectively. In other regions the trend of variation is not significant.

Table 1: The yearly mean maximum and minimum temperatures and the trend of variation of Tmax and Tmin in POM, Goroka, Kavieng, Nadzab and in Papua New Guinea.

	T max			**T min**		
	Mean T	**Zs**	**Sen's Slope**	**Mean T**	**Zs**	**Sen's Slope**
POM	31.47	**1.75**	**0.0126**	23.44	0.65	0.0061
Goroka	26.52	1.52	0.0112	15.8	**1.85**	**0.0159**
Kavieng	31.36	0.62	0.0258	24.23	**3.63**	**0.0225**
Nadzab	29.43	0.49	0.2912	22.92	-1.49	0.0064
PNG	30.43	**2.69**	**0.022**	23.69	**2.72**	**0.015**

2.1 Deforestation in Papua New Guinea

Tropical forests are important in mitigating climate change. Tropical forests play a crucial role in climate control by regulating temperature, rainfall, wind and cloud cover by storing large volumes of Carbon (IPCC, 2007). Release of large volumes of carbon in the atmosphere through human activity disturb the balance of the biosphere. Deforestation and forest fires release a large amount of carbon to the atmosphere (CIDA, 2001; Stern, 2007; Nepsted et al., 1999). About 80% of Papua New Guinea's land area is classified as forest. A decrease of 2.7% of forest area or 4.2% of tree cover loss is observed during 2002-2022 period. Forest loss in different regions is shown in Fig. 1. Forest loss was observed to be more in island region (red bars in Fig.1) and less in highland region (green bars in Fig.1). Forest loss in NCD (including POM) is 3.5, in Morobe (including Nadzab) is 2.4, in Eastern Highland (including Goroka) is 1.5 and in East New Britain (including Kavieng) is 9.

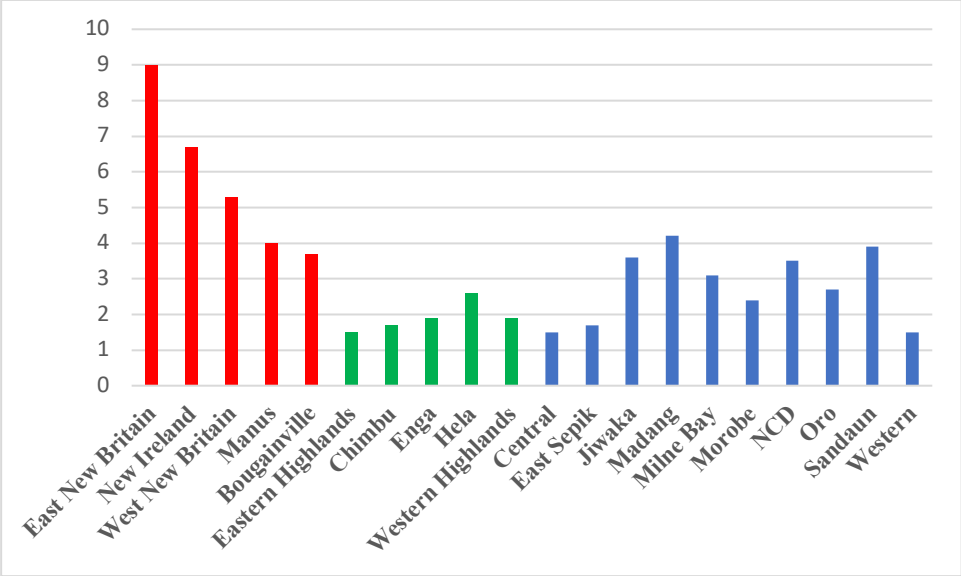

Fig. 1: The percentage of forest loss in different regions of Papua New Guinea

2.3 Rainfall Variability

The rainfall data for the period from 2001 -2020 is separated into wet season (from October to March) and dry season (from April to September) and the trend of variation is determined (Table 2). A significant positive trend of 3.27 mm/year is obtained in PNG and an increase in trend of 15.71mm/y in Nadzab during the dry season. In Goroka, an increase in trend of 8.63 mm/y is obtained during the wet season.

Table 2: The yearly mean rainfall and the trend of rainfall variability in POM, Goroka, Nadzab and Kavieng.

	Wet season			**Dry season**		
	Mean Annual Rainfall	**Zs**	**Sen's Slope**	**Mean Annual Rainfall**	**Zs**	**Sen's Slope**
POM	975	0	0.53	252	1.62	4.1
Goroka	1262	**3.37**	8.63	583	0	0.03
Kavieng	1736	-0.19	0.9	1499	-0.45	3.81
Nadzab	874	1.49	6.49	779	**2.43**	15.71
PNG	1212	1.13	4.59	778	**2.59**	3.27

2.4 Rainfall Anomaly Index

The yearly average values of rainfall are calculated for the period 2001-2020. The RAI for each year is calculated using equations (7) and (8). The years for which RAI values lie between -1 and +1 are considered 'Normal'. The year in which RAI value is in the range -3<RAI<-2 is taken as 'Dry' and RAI<-3 is considered as 'Extreme Dry'. Similarly, 2<RAI<3 and RAI>3 is considered 'Wet' and 'Extreme Wet' respectively. The calculated rainfall anomaly indices in the four regions are plotted in Fig. 2. Table 3 represents the years which fall in extreme dry, dry, normal, wet and extreme wet conditions. The percentage of periods where dry, wet and conditions prevail are calculated and tabulated in Table 4.

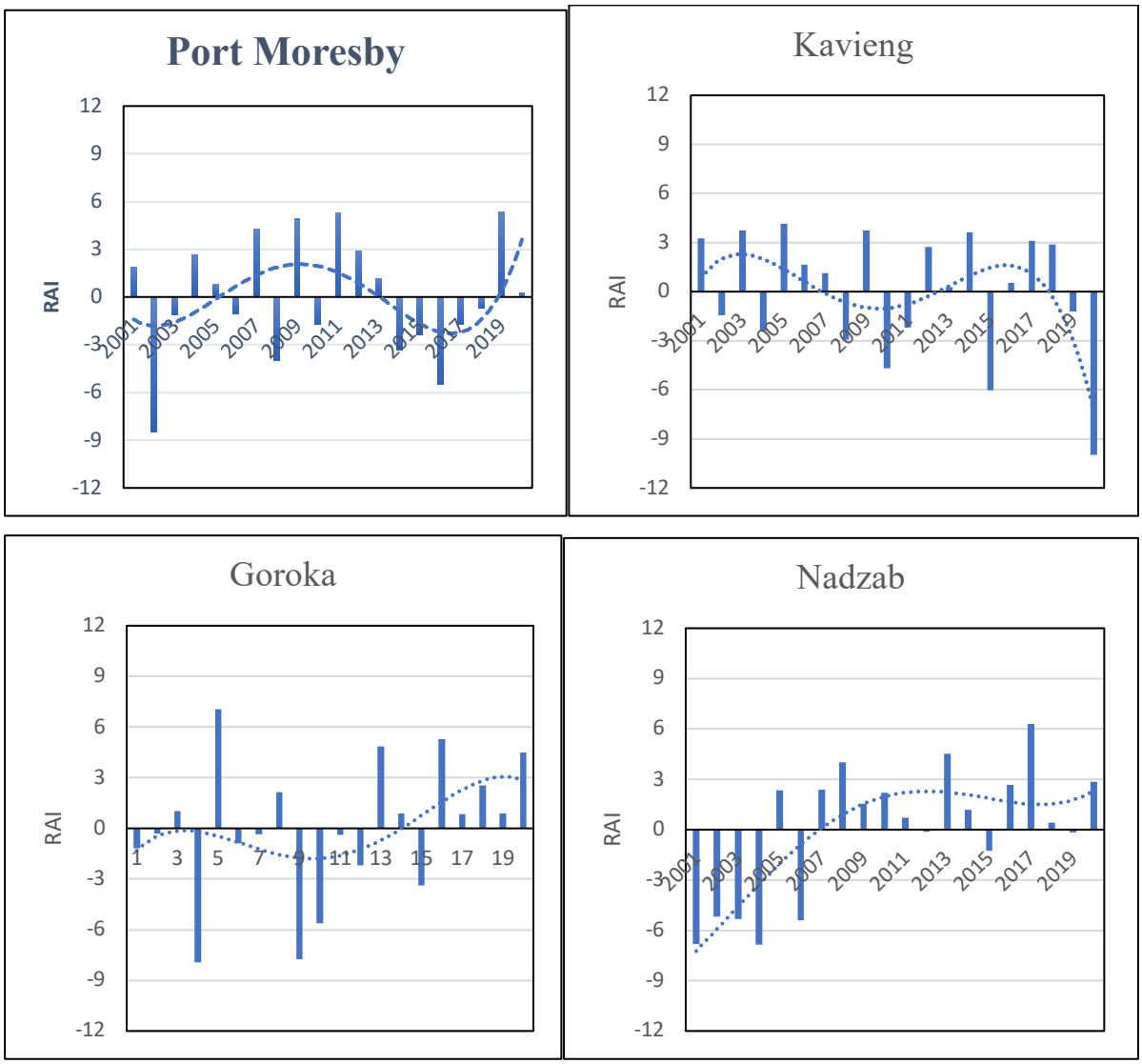

Fig. 2: Variation of RAI from 2001 to 2020 in POM, b) Goroka, c) Kavieng and d) Nadzab.

Table 3: Classification of years which are Dry, Extreme Dry, Wet and Extreme Wet for POM, Goroka, Kavieng and Nadzab for the period 2001-2020.

Region	Years				
	Extr. Dry	Dry	Normal	Wet	Extr. Wet
POM	2002, 2008, 2016	2014, 2015	2001, 2003, 2005, 2006, 2010, 2013, 2017, 2018, 2020	2004, 2012	2007, 2009, 2011, 2019

Goroka	2004, 2009, 2010	2012, 2015	2001, 2002, 2003, 2006, 2007, 2011, 2014, 2017, 2019	2008, 2018	2005, 2013, 2016, 2020
Nadzab	2001, 2002, 2003, 2004, 2006		2009, 2011, 2012, 2014, 2015, 2018, 2019	2005, 2007, 2010, 2016, 2020	2008, 2013, 2017
Kavieng	2010, 2015, 2020	2004, 2008, 2011	2002, 2006, 2007, 2013, 2016, 2019	2001, 2003, 2009, 2012, 2014, 2017, 2018	2005
PNG				2010	

Table 4: Percentage of years where Dry, Wet and Normal conditions prevail for the period 2001-2020.

	% of years where Dry, Wet and Normal conditions prevail		
	Dry	Wet	Normal
POM	25	30	45
Goroka	25	30	45
Nadzab	25	40	35
Kavieng	30	40	30
PNG	0	5	95

From Table 4, we can see that the rainfall condition is normal for 95% of time.

2.5 Climate variability due to El Nino-La Nina events

The Sea Surface Temperature (SST) anomaly in the Nino 2-3 region for the period 2001-2020 is used to find out the El Nino-La Nina events. Fig. 3 represents the variation of SST during the period of study. Anomaly greater than +5 is taken as El Nino event and less than -5 is taken as La Nina event. Table 5 gives the El Nino-La Nina years for the period of study.

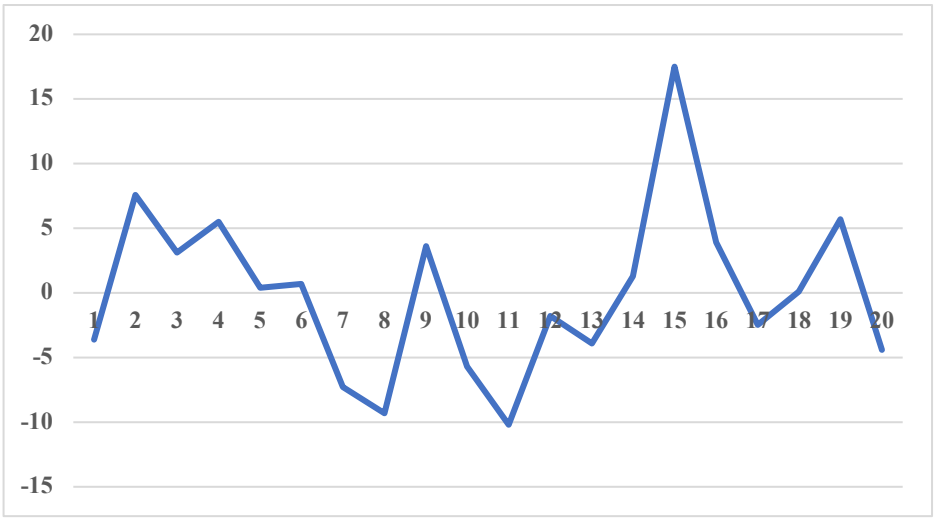

Fig. 3: Variation of Sea Surface Temperature Anomaly from 2001 to 2020.

Table 5: El Nino and La Nina years during 2001-2020.

El Nino				La Nina			
Weak	**Moderate**	**Strong**	**Very Strong**	**Weak**	**Moderate**	**Strong**	**Very Strong**
2004-05	2002-03		2015-16	2005-06	2011-12	2007-08	
2006-07	2009-10			2008-09	2020-21	2010-11	
2014-15				2016-17			
2018-19				2017-18			

2015 is a year of strong El Nino period where POM, Goroka and Kavieng experienced dry conditions. Forest loss is more in the Island region (Fig. 1) which includes Kavieng, which experienced extremely dry conditions (Table 3). During 2007-08 and 2010-11 years, La Nina conditions were strong (Table 5). In these periods, POM, Goroka and Nadzab experienced wet or extreme wet conditions (Table 3). But Kavieng experienced dry condition in these periods. PNG rainfall was found to be normal for 95% of years during the entire period of study (Table 5). This shows that even though the atmospheric temperature in different regions show an increase in trend, PNG's rainfall was not affected by global warming. Changes in rainfall are altered by El Nino-La Nina effects.

3. CONCLUSION

Climate change occurs due to global warming and other events such as El-Nino and La Nina events. Due to climate change, extreme conditions like extreme dry and extreme wet conditions occur which in turn affects agriculture and has connection with socio-economic systems of the country. The present study reveals that there is an increase in trend of atmospheric temperature with an increase of 0.02^0 C per year in Papua New Guinea. The rainfall is more or less the same everywhere except Goroka in wet season and Nadzab in dry season. Rainfall in POM, Goroka and Kavieng were found to be less during strong El-Nino events. Also, extreme wet conditions were observed in strong La Nina events.

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Watershed Characterization Approach to Redefine Bioregions: A Case Study at Moro and Iagifu Bioregions in Southern Highlands Province, Papua New Guinea

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Abstract: A watershed is the natural laboratory of water, soil, flora, and fauna. It is the land area where all precipitation drains to a lake, sea, or river through a common outlet. Demarcation of the watershed is generally performed using the Digital Elevation Model through topographic analysis. However, this method doesn't consider environmental processes and ecological relationships. This study employed the watershed characterization technique to define ecoregions and subsequently merge them to delineate a bioregion, utilizing geographical information science and systems (GIS) and remote sensing. It incorporated empirical and statistical data from six significant environmental variables: physio-geography, soil, climate, natural communities (focusing on flora), ecological processes, and hydrology. There is insufficient recognition for the watershed approach used in environmental impact assessments or analyses in Papua New Guinea. The study has shown that this technique can be highly effective, particularly in supporting watershed management practices, environmental planning, and natural resource management. To utilize this technique, one must understand the 'system of relationships' among the six significant ecological variables and how they interrelate and correlate within this dynamic bioregion. This research delineates more precise boundaries of the defined bioregions based on the scientific approach compared to the existing bioregions.

Keywords: Bioregion, Ecoregion, Environmental Impact Assessment, Geographic Information System, Watershed

1. INTRODUCTION

A watershed is a land area that drains rain or snowmelt water into a specific type of water body, such as streams, creeks, rivers, reservoirs, seas, or bays. Watershed characterization is a method that assesses and analyzes the physical, chemical, biological, social, and economic parameters for managing water, soil, and vegetation within the specific watershed region (Flotemersch et al., 2016). A bioregion is a geographical area characterized by its unique flora and fauna, ecology, and landforms, which a watershed can define. Remote Sensing (RS) is acquiring information about the Earth and providing data, primarily satellite data. The Geographical Information System (GIS) is another tool that handles spatial data, analyzes spatial relationships, and displays geographical data. Both tools are handy in watershed-related studies, including characterization, mapping, and management.

Recognizing the importance of watershed characterization can significantly aid in implementing policies that address the natural environment and mitigate its associated effects, particularly in countries like Papua New Guinea (PNG). Understanding the ecosystem or 'System of Relationships' among the significant environmental variables or parameters is vital when delineating a holistic bioregion (Vilhena & Antonelli, 2015). A bioregion has been defined in this study as a region consisting of a cluster of watersheds with heterogeneous landscapes on a larger scale. The environmental impact assessment or statement (EIA/EIS) report by the PNG-LNG stated that the existing bioregions in the Kikori Catchment were defined based on physio-geography, as the biota is usually reflected in the physical habitat (ExxonMobil, 2009).

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However, comparative analysis has shown that six significant environmental variables have been used to define a holistic bioregion, namely physio-geography, Soil, Climate, Natural Communities (including flora and fauna), Ecological Processes, and Hydrology (Accad et al., 2005). This study identified that the watershed characterization technique is the most suitable and convenient approach for incorporating the six significant environmental variables to redefine the existing bioregions. Many countries have sought to apply this watershed characterization approach to delineate their bioregions (Berg, 2005), while in PNG, the watershed characterization approach remains a concept that is yet to be fully understood and implemented in environmental planning and Monitoring Policies. The method of computing watershed characterization falls under RS and GIS. The Moro and Iagifu bioregions, along the corridor of the PNG-LNG upstream project area in the Southern Highlands Province of Papua New Guinea, were selected to conduct this research.

Five (5) research questions were formulated to guide the research and anticipate the expected outcomes, which will be based on the study's aim and objectives. They are (i) How can watershed characterization techniques be used to capture the required parameters for delineating a bioregion? (ii) What is the relationship between the stated parameters, and how can they be combined to delineate a bioregion for the study site? (iii) Why were some existing bioregions defined using only the physio-geography parameter rather than applying other major parameters? (iv) What benefits can the watershed characterization technique provide regarding environmental planning, natural resource management, environmental impact assessment and monitoring, environmental conservation, and other related areas? Moreover, (v) What comparisons can be made between the existing and delineated bioregions about the different approaches used? The primary objective of this research was to determine the definitive boundaries of existing bioregions using the watershed characterization technique. Four fundamental objectives were identified in this research. Firstly, the watershed boundaries will be delineated using area-wide and pour-point-based methods. Secondly, to delineate the ecoregions for the study area based on the six (6) major parameters that define a bioregion. The third objective was to combine and recombine the first two objectives according to their 'system of relationships' to delineate the bioregion and, ultimately, to compare and contrast the delineated bioregion with existing bioregions to appreciate the importance of the technique used.

2. STUDY LOCATION, MATERIALS, AND METHODS

2.1. Study location

Two bioregions within the Southern Highlands Province of Papua New Guinea define the study area. It is located approximately between the latitudes of 6º 16′ 34″ S and 6º 28′ 3″ S and the longitudes of 143º 6′ 51″ E and 143º 26′ 46″ E, respectively. The Moro Bioregion covers a land area of approximately 250 square kilometers and is home to the largest lake in Papua New Guinea, Lake Kutubu. The Iagifu Agogo Bioregion, in contrast, spans a land area of approximately 332 square kilometers (Figure 1). These bioregions are classified as karst bioregions because limestone features characterize the dominant landform. Karst is a distinctive terrain formed on soluble rock, characterized by landforms related to efficient underground drainage (Waltham, 2008).

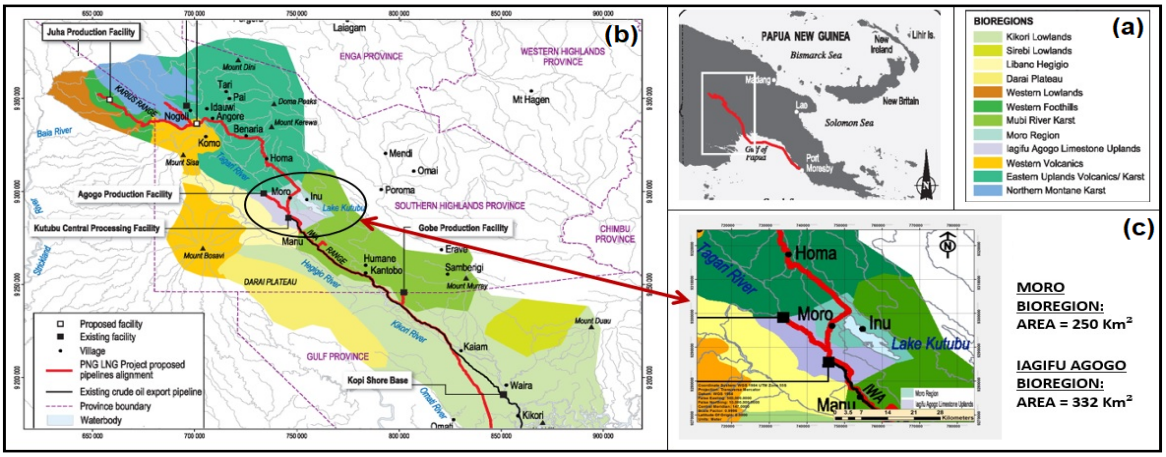

Fig.1. The locality map of the study Site: (a) Papua New Guinea, (b) Southern Highlands Province, and (c) Moro and Iagifu agogo bioregion (Source: PNG-LNG EIS Report and author's work).

2.2. Data used

Digital elevation models (DEMs) from SRTM and ASTER, with spatial resolutions of 90 m and 30 m, were used to compute the area- and point-based watersheds, respectively. Landsat8 optical land imager (OLI) data was used to classify land use and land cover within the bioregions. The vegetation cover was further classified using the 30 m resolution Landsat Tree Cover dataset. Topographic layers, climatic data, soil, and geology data were also incorporated from the Geo-book of PNGRIS. The details of these datasets are presented in Table 1. The leading software, ArcGIS 10.5, Erdas Imagine 8.5, MapInfo 11, and QGIS, were used to process all datasets.

Table 1. Data used for the study

Sl. No.	Data	Type	Scale/Resolution	Date	Source
1	Topographic Maps	Scanned	1:100,000	1966	School of Surveying and Land Studies, PNGUoT
2	PNG Topographic layers	Vector	MapInfo Table	2000	
3	Landsat 8	Raster	15m	2014	
4	SRTM DEM	Raster	90m	2001	
5	ASTER DEM	Raster	30m	2001	
6	PNGRIS	Geo-database	1:500,000	2010	
7	Landsat Tree Cover	Vegetation	30m	2000	

2.3. Methodology

The methodology involves data pre-processing, conversion and translation, creating and editing features, digitizing, sub-setting, feature extraction, and creating tables of attributes and geodatabases. Pre-processing was the initial step taken to analyze the data. It began by geo-referencing the scanned topographic map and other datasets to the WGS84 datum on UTM Zone 55 South. After that, the primary layers, such as roads, rivers, and built-up areas, were digitized. During that procedure, a table of attributes was also created for the vector files, which will later be added to or used in the geodatabase created in ArcGIS for editing and updating purposes. Additionally, all PNG topo layers and PNGRIS datasets were converted from tab files in MapInfo to shapefiles in ArcGIS. This was necessary because 85% of the analysis used ArcGIS software. Then, sub-setting and extraction were performed to clip out the Area of Interest (AOI) within the Southern Highlands Province (SHP). The DEM data was also clipped to extract the AOI of the study area.

The ArcGIS Spatial Analyst extension provides a toolset for analyzing and modeling spatial data. One of the tool sets under the Spatial Analyst extension is the Surface Analysis tool. DEMs of 90 m and 30 m were used to extract topographical features, including aspect, contours, hillshade, slope, and TIN (elevation), which were then used to compute the physio-geography ecoregion. A DEM of 90m was also used to delineate an area-wide watershed, capturing the extent of sub-watersheds within the area of interest (AOI). Then, a point-based watershed analysis was conducted to identify homogeneous catchment areas, which were used to delineate the diverse eco-regions for the study site. Image classification, also known as remote sensing classification, is a complex process that involves considering numerous factors. The significant steps of image classification include determining a suitable classification scheme, selecting training samples, selecting suitable classification approaches, performing post-classification processing, and assessing accuracy. Here, the research employs a strategy that involves unsupervised classification, followed by reclassification using supervised classification in Erdas Imagine 8.5 software. Spatial interpolation uses points with known values to estimate values at other points (Chang, 2006; Wu et al., 2005). In GIS applications, spatial interpolation is typically applied to a raster with estimates for all cells. Spatial interpolation is, therefore, a method of creating surface data from sample points, allowing the surface data to be used for analysis and modeling. The two datasets for the climatic variables, precipitation and temperature, were analyzed using the Inverse Distance Weighting (IDW) spatial interpolation (Chang, 2006). This method was applied to investigate how these two phenomena vary across the landscape within the study area and to examine

their correlation with other bioregional parameters. Thiessen Polygons or Voronoi Polygons were also computed from the point data of rainfall precipitation to calculate the mean rainfall within each eco-watershed region.

About 60% of the study output was computed using these map overlay and map manipulation processes. This is a critical stage at which understanding the 'System of Relationships' or the ecosystem among the six significant environmental variables becomes crucial. The overlay operations depend on the source and target zones' geometric properties (points, lines, and polygons) (Chang, 2006). It superimposes the target zone on the source zone to obtain the proportion of each source zone in each target zone. All overlay operations are based on Boolean connectors. Four standard overlay methods exist: Union, Intersect, Symmetrical Difference, and Identity. The union preserves all features from both input layers. In contrast, the Intersect method preserves only those features that fall within the typical area extent of the two input layers. The Symmetrical difference method preserves areas common to only one of the inputs, and the Identity method preserves only features that fall within the area extent of the layer defined as the input layer. The Map Manipulation technique involves Dissolve, Clip, Append, Select, Eliminate, Update, Erase, and Split (Chang, 2006). In this analysis, only two layers combine spatial and attribute data from the two input layers into a single layer. Integrating map overlays and map manipulations has provided an avenue for delineating the Eco-Watershed Regions.

3. RESULTS AND DISCUSSIONS

The results produced under the six environmental variables were used to delineate the ecological regions. Ecoregions can be flexibly combined and reconfigured in various ways to accommodate changing conditions and specific purposes (Griffith et al., 1999). In this study, the ecoregions were combined to delineate the bioregions. This was all possible because watershed characterization sets the foundation for demarcating these ecoregions into bioregions.

3.1. Watershed characterization

The initial results were presented in an Area-wide watershed and a Point-based watershed. Both analyses followed the same procedures: using the DEM to compute flow directions, followed by flow accumulation. From there, stream order, streamline, and stream link were calculated to determine an Area-wide watershed (Figure 2a) and a Point-Based watershed (Figure 2b).

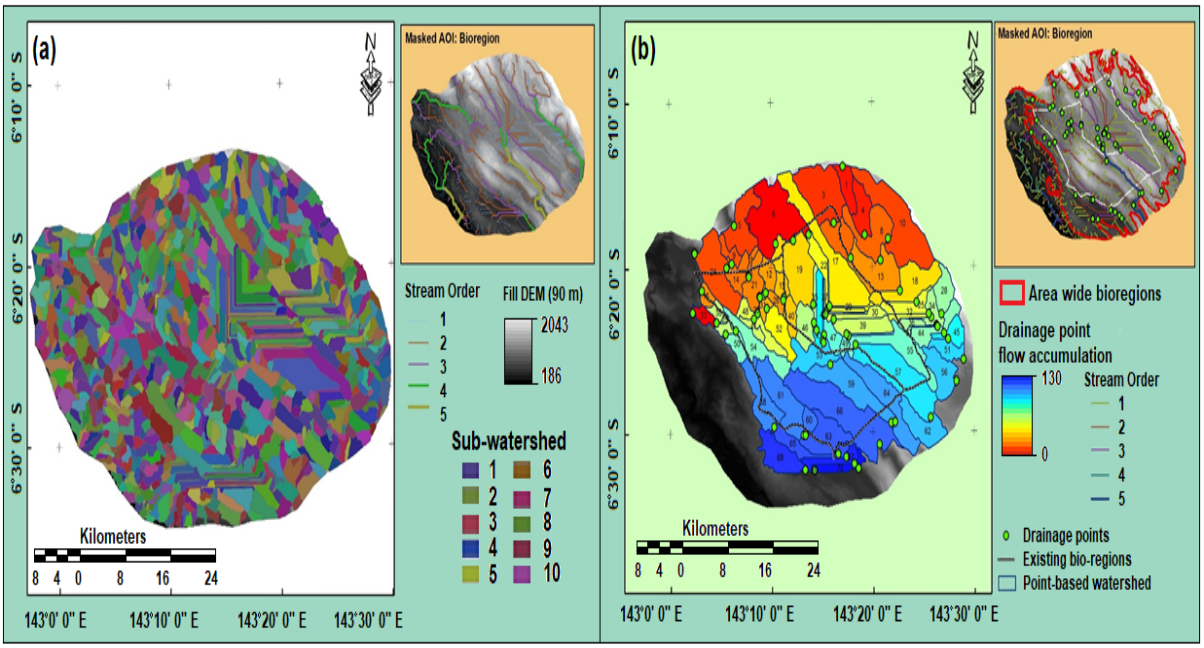

Fig.2. Area-Wide Watershed and Point-Based Watershed Delineations

The morphometric parameters, Bifurcation Ratio (Rb) and Drainage Density (Dd), were also developed to understand the general behavior of the watersheds (Pal et al., 2012). The results are presented in Tables 2 and 3.

Table 2. Calculating Bifurcation Ratio (Rb)

Stream Orders	Stream Length (km)	No/Streams per Order (Nu)	Bifurcation Ration (Rb)
1st	466	248	2.084
2nd	248	119	1.469
3rd	121	81	1.5
4th	44	54	4.5
5th	21	12	1
Total	**900 km**	**514 (number)**	**Mean Rb = 2.111**

Table 3. Watershed Basin Statistics

Watershed (Basin)	Area in Km^2	Perimeter (Km)	Total Length of Stream Orders	Drainage density
Eco-Hydro Region	662	705	900 Km	1.36 Km^{-1}

The bifurcation ratio has no dimension and is formulated as the ratio between the number of streams of one order and those of the next higher order in a drainage network (Strager et al, 2010). This ratio is of fundamental importance in drainage basin analysis, as it is the primary parameter for linking the hydrological regime of a watershed under topological and climatic conditions, and it also aids in interpreting the basin's shape and deciphering runoff behavior (Biswas et al., 1999). For instance, Rb of 2.111 can be classed as a drainage basin that is flat or rolling on the landscape. Whereas Drainage density (Dd) is the stream length per unit area in the region of the watershed (Kinthada et al., 2013), it is a better quantitative expression of the dissection and analysis of landforms (Pareta & Pareta, 2011). It measures how well or how poorly a watershed is drained by stream channels. Based on the results, it can be seen that the Dd for the eco-hydro region is 1.36 km², corresponding to an area of a basin that has Ied high Infiltration and low surface runoff, as evident In Its topographical and physio-geographical nature. This analysis falls under the realm of hydrology, considering altitude. The results yielded three transitional boundaries, which were used to delineate the study's Conducive Eco-Hydro Region (Figure 3).

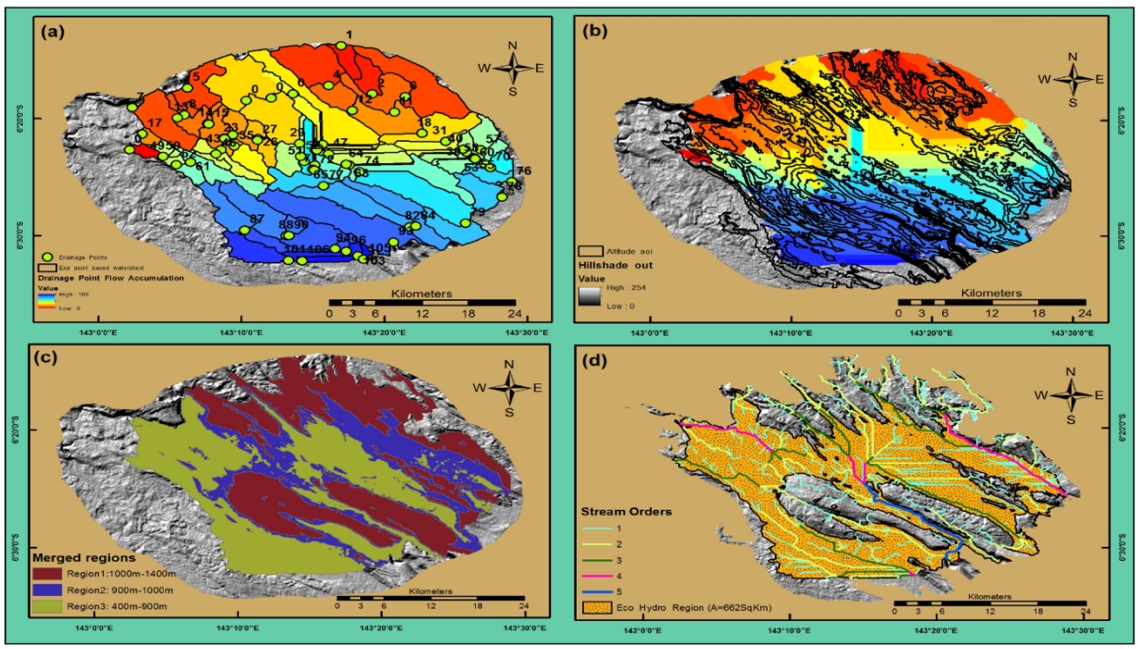

Fig. 3. Delineation of Conducive Eco-Hydro Regions: (a) Point-based watershed, (b) Sub-watershed class altitude, (c) Merged sub-watershed, and (d) Conducive Eco-hydro region

3.2. Physio-geographical Ecoregion

Under physio-geography, three main constituents, namely Topography, Landform, and Geology, have been used to delineate the physio-geographical ecoregion. The topographical features extracted from the SRTM 90-meter resolution dataset were Slope, Aspect, Hill-shade (or shaded relief), Contours, and Elevation (TIN). These topo layers were used because they provide a rigid landscape and terrain demarcation boundary within the area-wide bioregion (Jenson & Domingue, 1988) (Table 4 and Figure 4).

Table 4. Extraction of Topographical Layers

Sl. no.	Topographical layers	Feature extractions	Descriptions
1	Slope	15 degrees - 61 degrees	Represents the ridgelines for watershed boundaries
2	Aspect	Southwest & Northeast side	Captures of shaded areas of valleys and drainage systems
3	Hill shade	Shaded Relief	Terrain simulation with topo-features
4	Contours	50m interval	Simulates elevation intervals
5	Elevation (TIN)	250m – 2000m	Watershed drainage areas

The lithology of an area best describes its geology. This study has utilized referenced PNGRIS data (scale: 1:500,000) and identified six major lithology classes. This is evident in Table 5. The lithology "Tmd1" was recognized as the dominant feature within the area-wide watershed. These six classes were merged to delineate the Lithology–Eco watersheds. The results are presented in Figure 5. The landform data was also obtained from PNGRIS with the exact resolution. The three significant landforms were identified within the area of interest (AOI) or area-wide watershed, where Landform 55 (Polygonal Karst) covers most of the area. This is illustrated in Table 6 and Figure 6 accordingly. This type of landform is referred to as a braided stream system resulting from highly permeable material with underground drainage channels and is commonly characterized by sinkholes (Paine & Kiser, 2003). Generally, the lithology is the geological factor that determines the type of landforms. Therefore, Lithology Tmd1 (Massive-thick-bedded limestone) describes the characteristics of this type of limestone. Due to weathering and erosion over time, it is exhibited in Landform 55 of the polygonal karst region. Thus, the areas or boundaries within the intersection between the delineated lithology ecoregion and landform ecoregion were dissolved to aggregate the overall region, known as the Physio-geographical Ecoregion, for the study site. This is illustrated in Figure 7.

Table 5. Lithological Features in Area of Interest (AOI)

No	Lithology Type	Feature Extracted	Area (Km^2)
1	Lithology Qa4	Gravel, sand, silt, mud, clay, peat	109
2	Lithology Qv1	Basaltic & andesite lava, agglomerate tuff	63
3	Lithology TQK2	Volcaniclastic andesitic & basaltic breccia	121
4	Lithology Tmd1	Massive to thick-bedded limestone	707
5	Lithology Tmup2	Blue-grey calcareous mudstone, shale	102
6	Water (Lake Kutubu)	Waterbody	52

Table 6. Landform features in the area of interest (AOI)

Sl. No.	Landform Type	Feature Extracted	Descriptions	Area (Km^2)
1	Landform 55	Polygonal Karst	Plateaux or broad ridges of limestone covered with numerous rugged hills	680
2	Landform 51	Mountain & Hills	Weak or no structural control	126
3	Landform 32	Dissected volcanic foot-slopes	Little-dissected volcanic foot-slopes and volcano alluvial fans	70

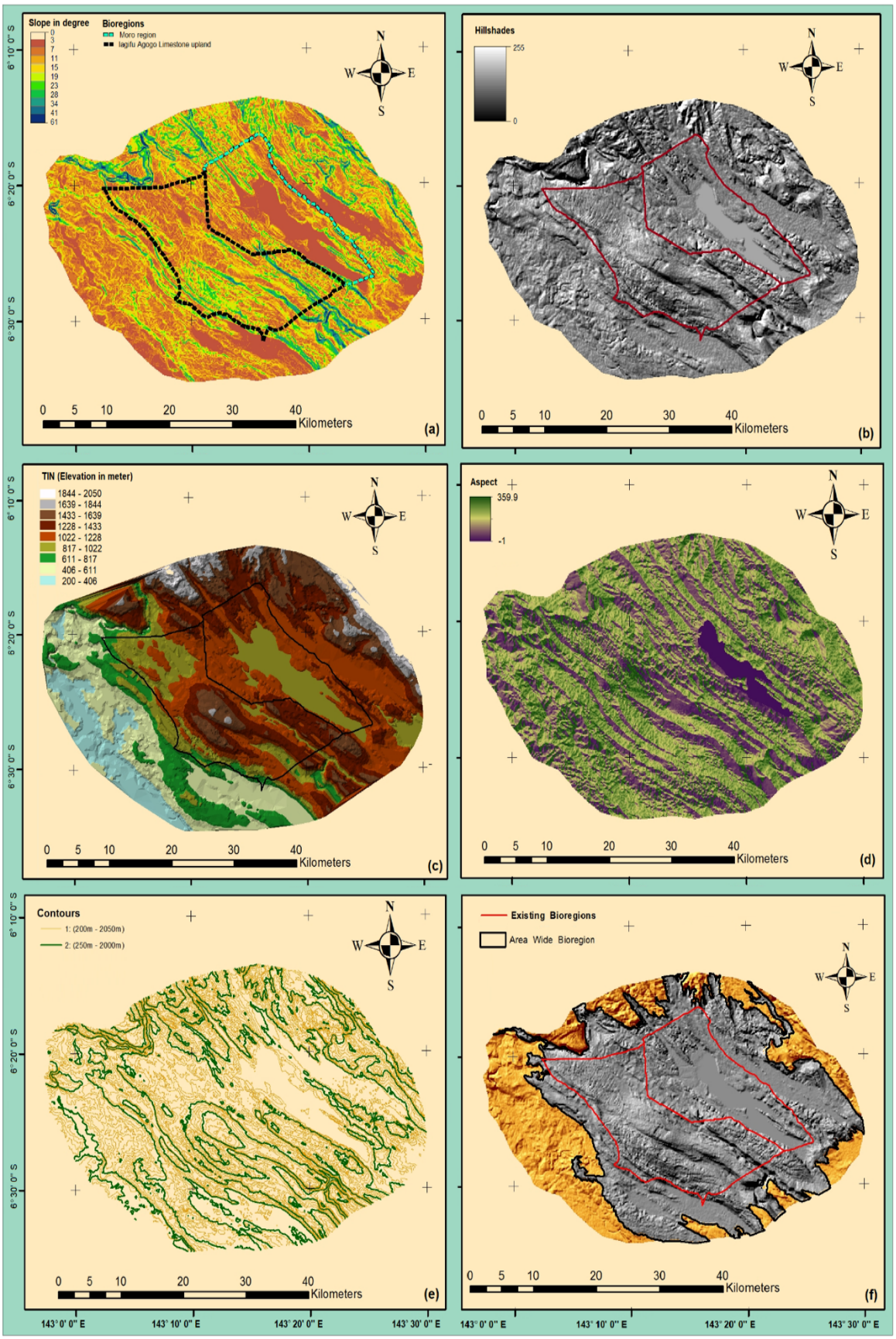

Fig. 4. Topographical features to calculate Area-Wide Bioregion: (a) Slope characteristics, (b) Hill shades, (c) TIN, (d) Aspect, (e) Contours, and (f) Existing bioregions within Area-Wide bioregions.

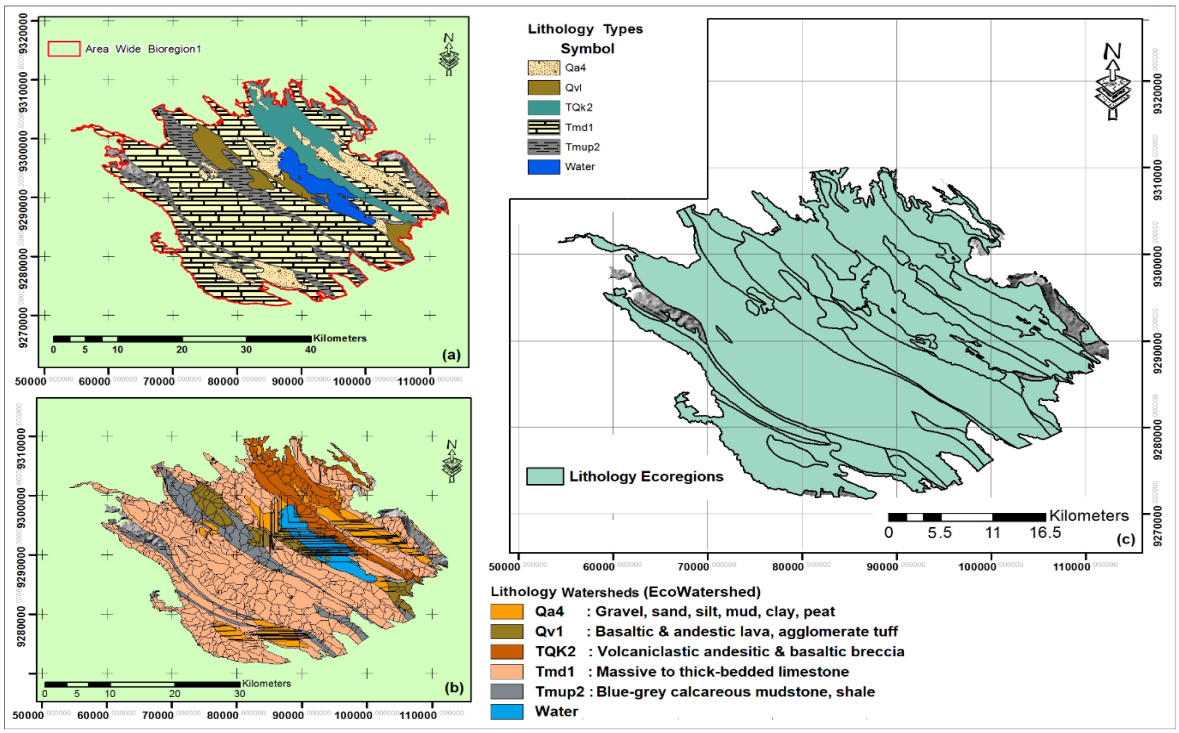

Fig. 5. Delineation of Ecoregion from lithology: (a) Lithology types, (b) Lithology intersected with Area-Wide Watershed, and (c) Delineated Lithology Ecoregion

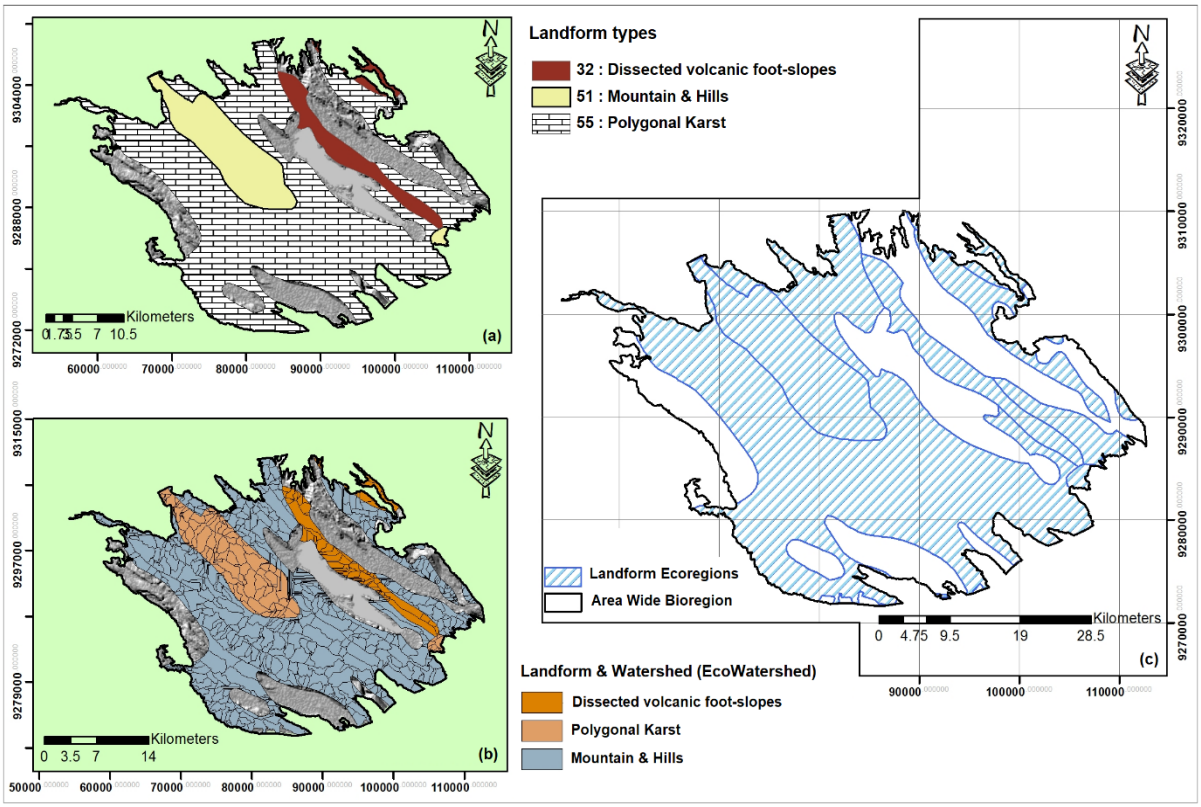

Fig. 6. Delineation of Ecoregion from Landform: (a) Landform types in Area Wide Bioregion, (b) Landform intersect with Area Wide Watershed in an Area Wide Bioregion, (c) Delineated Landform ecoregion.

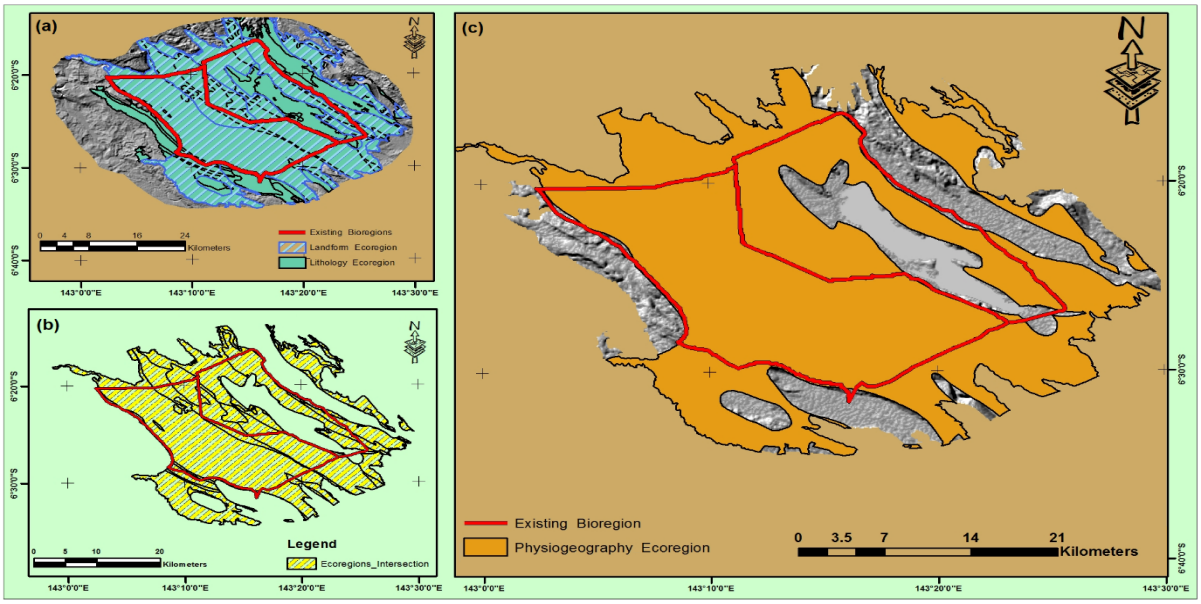

Fig. 7. Delineation of Ecoregion from Physio-geography: (a) Overlay of Lithology Ecoregion and Landform Ecoregion, (b) Lithology and Landform intersection, and (c) Physio-geographical ecoregion

3.3. Soil characteristics within the Physio-geographical Ecoregion

The study independently examined soil as one of the six significant environmental variables. This is because soil is an ecosystem component of many ecoregion properties, including vegetation and land use (Johnson et al., 1995). Regarding soil descriptors, the study has focused on Soil Type and Soil Texture. Six major soil types are identified within the physio-geography ecoregion, of which Eutropepts is the most dominant. Eight soil textures were identified, of which Sandy Clay appears to be the most dominant, occurring within an elevation range of 1100 m to 1200 m. The results are presented in Figure 8. The soil data analysis utilized physio-geography ecoregions and sub-watersheds merged based on altitude.

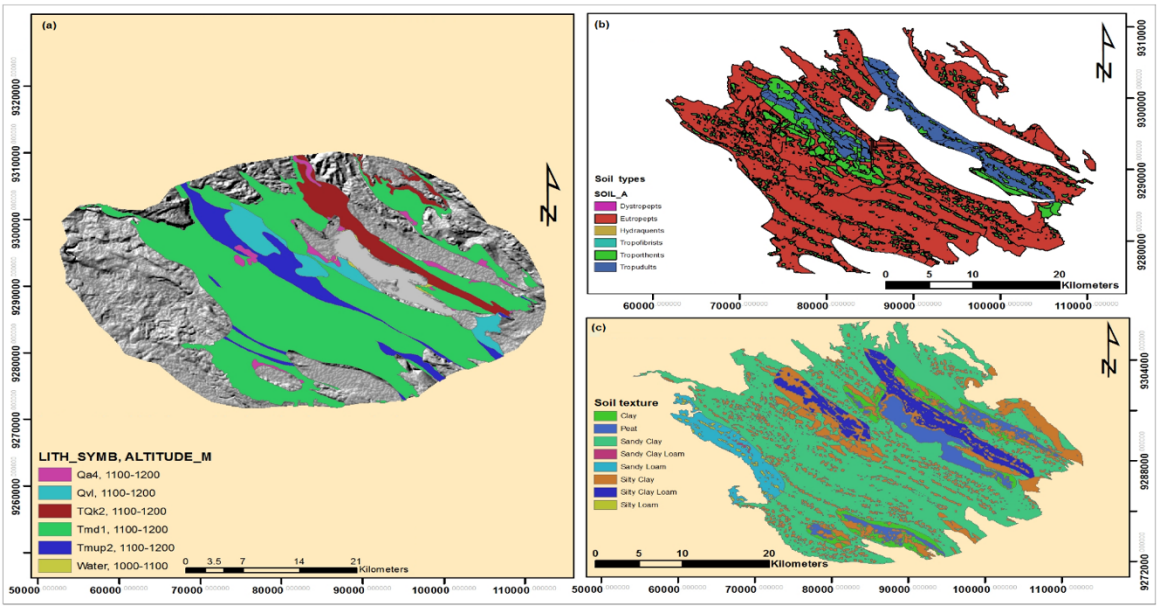

Fig. 8. Delineating Soil within Physio-geographical Ecoregion: (a) Physio-geographical Ecoregion merged with altitude, (b) Soil type-A within Physio-geographical Ecoregion, and (c)Soil texture within Physio-geographical Ecoregion

3.4. Sub-Transitional Climate Zone for Eco-Watersheds

Climate largely determines the boundaries of ecosystems. In tropical regions, rainfall, precipitation, and temperature are the primary factors considered, as they are typically used to define terrestrial biomes. Furthermore, the inner structure of the ecoregion is organized as a series of intersecting gradients; temperature and precipitation change with elevation in alternating belts of vegetation along windward and leeward sides of a parallel series of mountain ranges, with biodiversity thinning towards the edges (Griffith et al., 1999; Dinerstein et al., 1995). As such, the interrelationships between precipitation, temperature, elevation, and vegetation were analyzed to help delineate holistic ecoregions, which enabled the computation of the final biome region, commonly referred to as a bioregion. The climatic data were obtained from PNGRIS in 2000 and analyzed, as shown in Table 7.

Table 7. Extracting Rainfall Precipitation and Temperature for the AOI

No.	Climate Data	Feature Extracted	Descriptions
1	Rainfall (mm)	(3400mm) – (4700mm) with every 100mm interval	Gives the annual rainfall but does not specify which month the values were obtained.
2	Minimum Temperature	(11°C - 20°C) With every 1 °C interval	Minimum temperature range found within the delineated bioregion
3	Maximum Temperature	(22°C - 31°C) With every 1 °C interval	Max. The temperature range found within the delineated bioregion.

The rainfall data were merged based on similarities in the attribute table, and the average rainfall in millimeters for each rainfall range (3400 mm – 4700 mm) was estimated. After that, the feature class was converted to point data for spatial interpolation. Inverse Distance Weighted (IDW) interpolation was applied to the overall rainfall data to produce the study site's mean or average rainfall data (Dobesch et al., 2013). IDW was also performed separately on the minimum and maximum temperature datasets (Samanta et al., 2012). Their outputs were merged to produce the final result of Average Temperature across the study site. The IDW results for the annual average rainfall precipitation and average temperature were intersected to observe the correlation between these two phenomena and, more specifically, to help identify the physical transition zones for delineating the ecoregions within the biome. The statistics output from this intersection are presented in Table 8. In general terms, there is a negative correlation between rainfall and temperature. For instance, as the temperature increases, the rainfall decreases and vice versa. However, the results from this analysis show that the annual average rainfall precipitation remained constant at approximately 4350 mm, while its temperature gradually increased from 13.5 °C to 19.5 °C and from 27.5 °C to 30.5 °C. There was a drop in rainfall (3550 mm) when the temperature was at 24.5 °C. This is a classic example of regional weather variations (Samanta et al., 2012), such as an ecoregion or bioregion.

Table 8. Average temperature and rainfall data within the AOI

Mean Temperature (°C)	Average yearly total rainfall (mm)	Mean Temperature (°C)	Average yearly total rainfall (mm)
11.5	3750	22.5	4050
12.5	4450	23.5	3850
13.5	4350	24.5	3550
14.5	4350	25.5	4350
15.5	4350	26.5	4250
16.5	4350	27.5	4350
17.5	4350	28.5	4350
18.5	4350	29.5	4350
19.5	4350	30.5	4350

Hence, the study area is in a tropical region subject to the seasonal influence of the Northwest Monsoon (December–March) and the Southeast Trade Winds (May–October). Based on the statistics in Table 9, a line graph was created that resembles a biome similar to the Tropical Rainforest. This graph is illustrated in Figure 10. Therefore, the study has concluded that, regardless of the seasonal rainfall over the study area, it is the tropical rainforest cover, having its own Micro-Climate has seemed to influence the amount of precipitation and evapotranspiration in terms of regulating the ecological processes such as water cycle, nutrient cycle, and energy flow, taking into consideration of the topography and elevation within a region (watershed, ecoregion, or bioregion) (Nowak, 2018), as seen in this case study. The values obtained for the phenomenon were then used to delineate the temporal transition zones. Two zones were delineated; one zone used data from 13.5 °C to 19.5 °C, and the other used data from 27.5 °C to 30.5 °C, where the rainfall precipitation is constant at 4350 mm. The process began by creating a new layer for each dataset. After that, both layers were intersected to delineate a region based on average precipitation and temperature. The research described this region as a transitional Climate Zone Delineation within a bioregion (Figure 9).

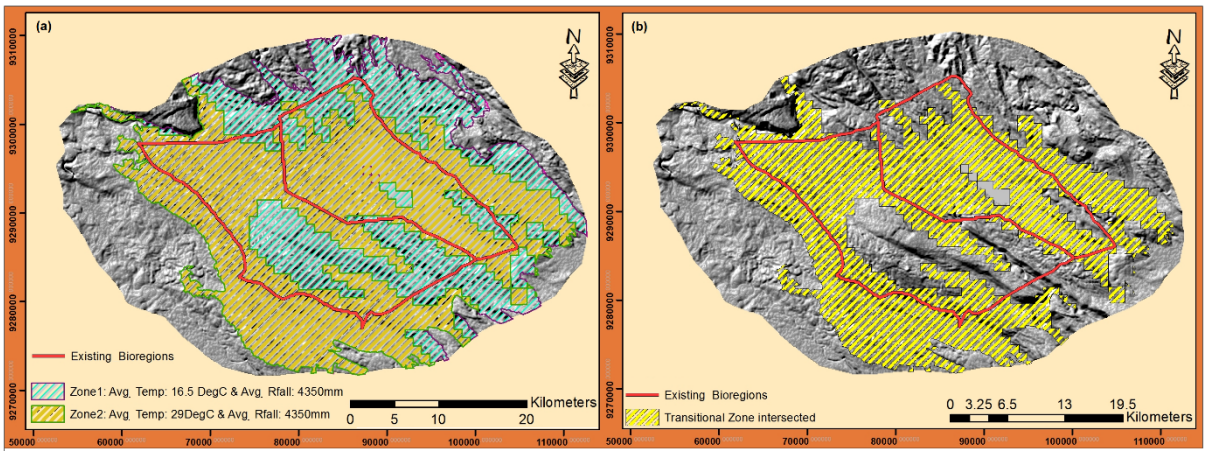

Fig. 9. Delineation of transitional climate zone: (a) Overlay of average rainfall (4350 mm) and temperature (16.5º °C & 29º °C), and (b) Transitional climate zone

3.5. Eco-Watershed Region Delineation

Ecological Process, considered in this study as one of the six significant environmental variables defining a bioregion, was analyzed at the watershed scale. The ecological process encompasses the water cycle, nutrient cycle, energy flow, community dynamics, and succession, all vital for sustaining biodiversity (Acreman, 1999). Thus, biodiversity varies from place to place or from region to region, and so watershed divides have been applied to naturally demarcate the biodiversity regions into ecoregions (Bothale et al., 1998). In line with the study analysis, the water cycle was considered because precipitation and surface runoffs play vital roles in the cycling of different elements within the ecosystem (Bennett et al., 2009). Surface runoff was already computed in the first part of this study as part of the watershed characterization. This part is an extension of precipitation analysis that identifies rainfall estimation within sub-watershed levels. The process began by utilizing the rainfall point data to create Thiessen Polygons or Voronoi Polygons. The Voronoi polygons within the sub-watersheds were merged based on similarities in their attribute tables. Its output was then intersected with the Transitional Climate Zone data, taking elevation or altitude into account this time. The study has termed this output as the Eco-Watershed Region. Hence, it represents an ecological region characterized by watersheds. Table 9 and Figure 10 accordingly present the statistical output from this analysis. The production of the Voronoi polygon reveals 13 classes of rainfall precipitation, ranging from 3400 mm to 4700 mm, which are distributed across the study site. However, the focus is within the existing bioregion, so intersecting this data with the transitional climate zone data resulted in the Eco-Watershed Region. In this region, the average rainfall precipitation throughout the year is 4350mm with a mean temperature of 16.5 °C, which is distributed throughout the bioregion with altitudes ranging from 1000 meters to 1100 meters (Figure 10)

Table 9. Table of Attributes for Eco-Watershed Region

Rainfall range (mm)	Average Rainfall (mm)	Perimeter (km)	Area (km^2)	Average Temp (°C)
4300 - 4400	4350	541	737	16.5

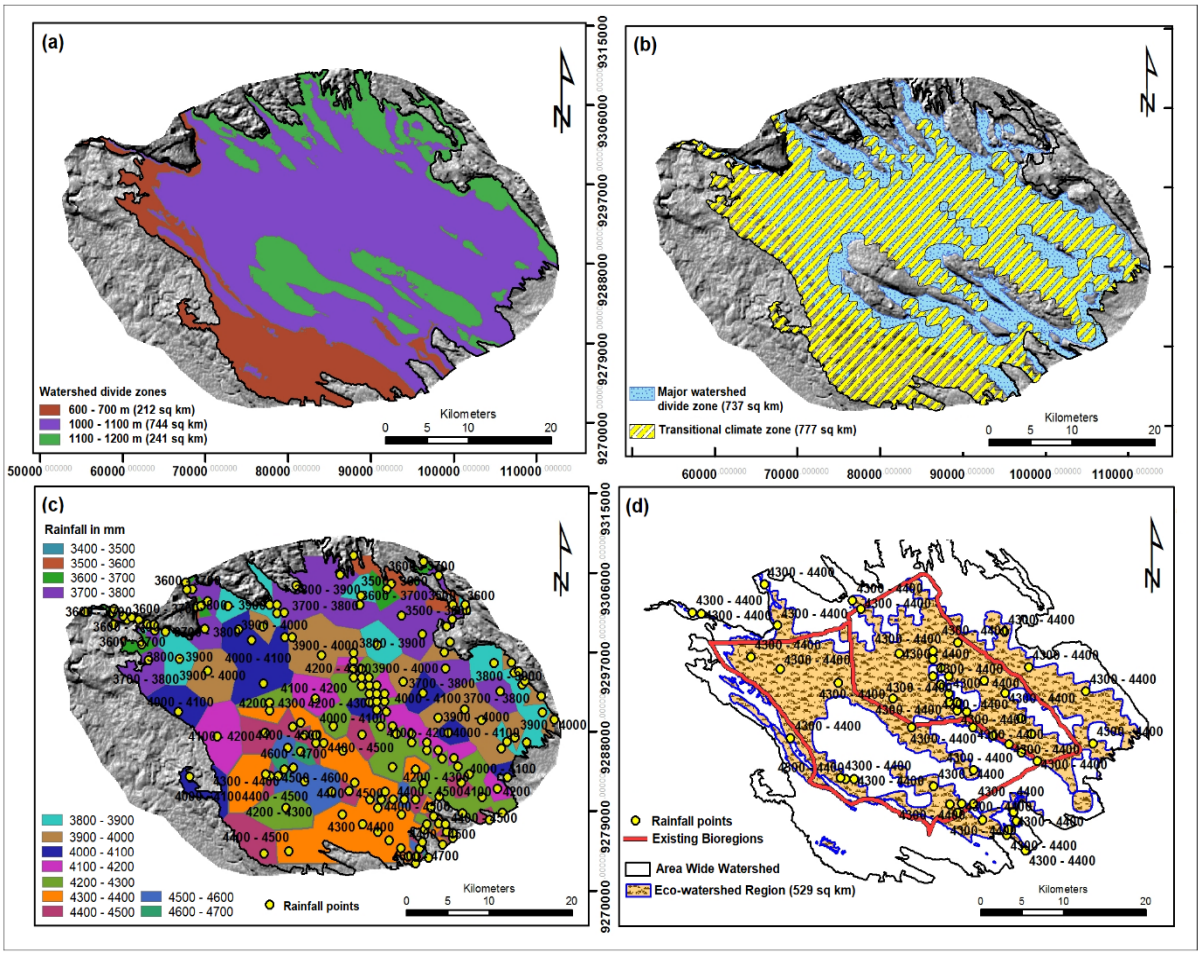

Fig. 10. Delineation of Eco-Watershed Region: (a) Watershed divider, (b) Intersection of transitional climate zone with central watershed divider, (c) interpolated rainfall using Thiessen polygon, and (d) Eco-watershed region based on water dividers and transitional climate zone

3.6. Natural Communities (Forest Cover)

Another important environmental parameter to consider when defining an ecoregion or bioregion is the presence of the flora and fauna, which are regarded as biotic factors and their relationships with the abiotic factors within an ecosystem. Since the study focuses on delineating ecoregions into bioregions on a larger scale, it has considered forest cover because it plays a significant role in natural communities' dominant feature (Connell & Slatyer, 1977). As defined in climatic analysis, the tropical rainforest is the primary vegetation cover that has provided a basis for classifying forests using the PNG Forest Inventory Management System (FIMS). The PNG FIMS is used to classify forests based on their altitude or elevation above mean sea level, measured in meters (m). The forest dataset was obtained from MOD44B Vegetation Cover data from the MODIS Satellite over the Southern Highlands Province (SHP) in 2000. This dataset was then intersected with the watershed ecoregion, yielding four major forest classes across the study area (Table 10).

Table 10. Forest Classification on Altitude

No	Altitude (meters)	Descriptions (PNG FIMS)	Area (Km^2)	Perimeter (Km)
1	300 – 700	Low-altitude forests on plains and fans	20, 141	378
2	700 – 1000	Low-altitude forests on uplands	56, 945	887
3	1000 – 1200	Low Montane Forests	31, 215	1014
4	1200 - 1500	Mid-Montane Forests	8, 894	487

3.7. Forest Ecoregion Delineation

After combining all the analyses, the final result for the forest classification was then delineated into an ecoregion, which can be seen by integrating the average rainfall in a watershed. This is illustrated in Figure 13. The computed forest ecoregion within the watersheds has four distinct classes throughout the terrain, with undulating topography dominated by karst regions. The average annual precipitation varies within each watershed, but not to a great extent. The perimeters computed using the altitude to classify the forest have been considered here as transition zones for the forest classes and for other upland ecotones and thus were used to delineate the boundary of the bioregion for the AOI, together with other delineated ecoregion parameters. Regarding physio-geographical changes, an increase in altitude typically reduces the size of forest tree crowns (Nowak, 2018).

3.8. Forest on Physio-geography

The forest classes were then intersected with the physio-geography ecoregion to understand the natural structure of the forest within the AOI. From this result, it was observed that the tropical rainforest classes were dominated by Landforms 32 and 55, which are characterized by limestone with varying degrees of karstification. Due to its geological structure, most low-altitude forests on uplands (700m – 1000m) appear open, giving the impression of an open forest. This output was then compared with the rainfall within the watershed regions to help understand the influence of climate on the forests.

3.9. Classified Forests within Watersheds (Voronoi)

The classified open forests were then intersected with the rainfall estimates within a watershed to analyze the relationship between the natural growth and distribution of the forests from different altitudes. Their results have shown that most watersheds are dominated by low-altitude forests on plains and fans, spreading across the bioregion, with few low-altitude forests on uplands. The rainfall distribution varies from watershed to watershed; however, it appears to have a limited influence on the forest cover, in contrast to altitude, topography, soil, and geology, which significantly impact the forest's natural structure and classification within the study area. For example, the increase in altitude has affected the species diversity and tree sizes, which tend to decrease.

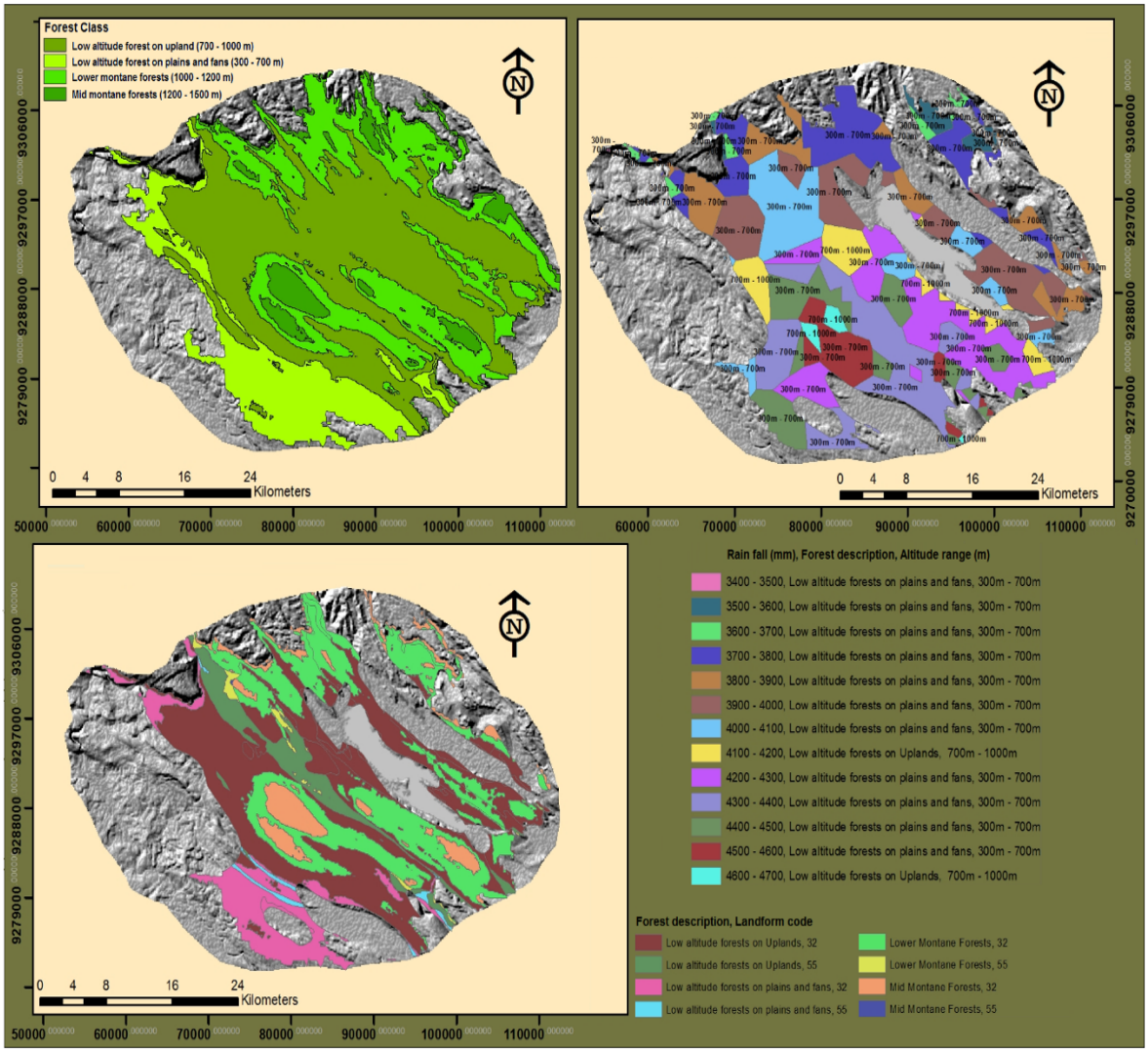

Fig.11. Delineation of Forest Ecoregion: (a) Forest classification within the bioregion based on altitude, (b) Combination of forest and rainfall, and (c) Intersection of forest with physio-geography.

3.10. Heterogeneous Landscape Delineation

The study here focused on merging all the delineated ecoregions (homogeneous landscapes) into a bioregion. A bioregion can be classified as a heterogeneous landscape on a larger watershed scale (Hartwell & Welsh, 1994; Waissbluth, 2016). The approach taken here to understand environmental diversity within heterogeneous and homogeneous landscapes is using the Land Use and Land Cover (LULC) classification method. Environmental classification at a larger scale can capture diverse ecological variables, including different vegetation cover types, agricultural land, water bodies, human-built structures, and topographical features (Lu & Weng, 2007). The analysis began by mapping the LULC for the entire study area. The LULC analysis used a 15-meter resolution Landsat 8 image from 2000. It has seven spectral bands, which have been used to perform the ISODATA unsupervised classification by assigning 50 classes with a maximum iteration of 6. The target LULC classes selected were: lake/water body, marshland/wetlands, clear land area, light vegetation, dense vegetation, cloud cover and haze, and built-up zones. After merging the classes in the signature editor, the unsupervised image was reclassified by performing supervised classification. Finally, recoding was performed using the secondary data sources, resulting in an overall classification accuracy of 93.33%. This is illustrated in Table 11 and Figure 12, respectively.

Table 11. LULC Classification Statistics for Heterogeneous Landscape (Area Wide)

No	Class Name	Area (hectares)	Area (%)
1	Lake / Water Body	5133.02	4.29
2	Marsh Land / Wetlands	8769.33	7.33
3	Clear Land Area	5106.00	4.27
4	Light Vegetation	43344.16	36.22
5	Dense Vegetation	37488.94	31.33
6	Cloud Cover and Haze	18138.78	15.16
7	Built-Ups	1676.18	1.40

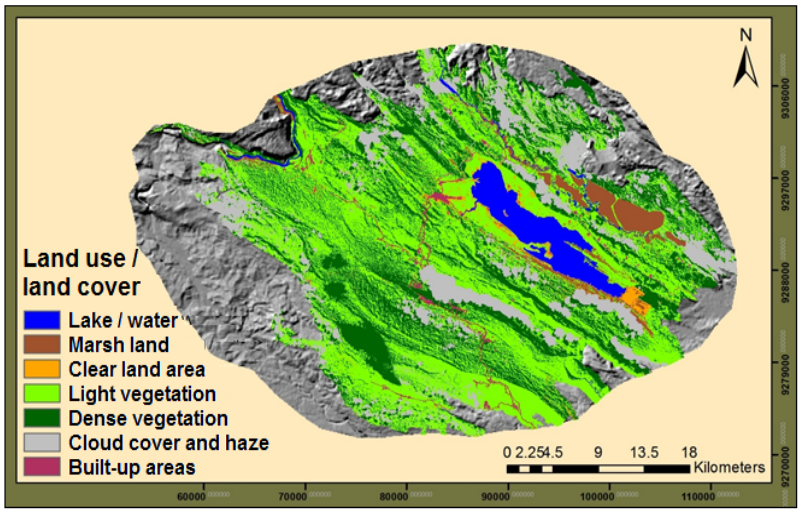

Fig.12. Heterogeneous Landscape Delineation (Area-Wide Bioregion)

3.11. Eco-Watershed Region Classification

The heterogeneous landscape was then intersected with the eco-watershed region, which was computed under the water cycle analysis to extract the Land Use and Land Cover within the catchment zone. The result still displays vegetation diversity, capturing all seven significant classes. This heterogeneous eco-watershed landscape was created as it is vital in providing a holistic definition of bioregion delineation (Omernik, 2004). The boundaries of the eco-watershed heterogeneous landscape also depict transition zones (Figure 13 and Table 12).

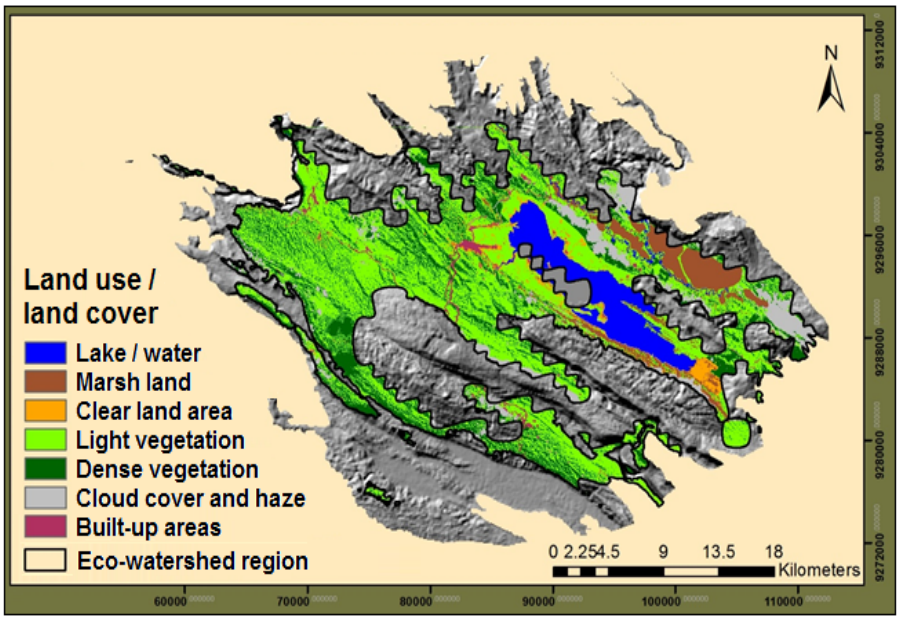

Fig. 13. Eco-Watershed Heterogeneous Landscape Delineation

Table 12. LULC Classification Statistics for Eco-watershed Region

No	Class Name	Area (hectares)	Area (%)
1	Lake / Water Body	4634.71	8.79
2	Marshland / Wetlands	3853.22	7.31
3	Clear Land Area	1205.12	2.29
4	Light Vegetation	25602.73	48.55
5	Dense Vegetation	12227.40	23.19
6	Cloud Cover and Haze	4290.48	8.14
7	Built-Ups	920.97	1.75

3.12. Bioregion Delineation

The study delineates a holistic bioregion by considering the six main environmental variables and understanding how their 'system of relationships' correlates and interrelates (Nas & Berktay, 2010). The watershed characterization technique is the most suitable and convenient approach. The watershed characterization technique provided the avenue in which the following ecoregions were delineated, namely (i) Conducive Eco-Hydro Region, (ii) Physio-geographical Ecoregion, (iii) Transitional Climate Zone, (iv) Eco-Watershed Region, (v) Forest Ecoregion, and (vi) Eco-Watershed Heterogeneous Landscape. Practically, ecoregions can be flexibly combined and recombined in various configurations to accommodate changing conditions and specific purposes (Bailey, 1983). The delineated ecoregions fit the homogeneous landscape, environment, or climate description. These delineated ecoregions were then merged or intersected to delineate the bioregion for the study site (Figure 14).

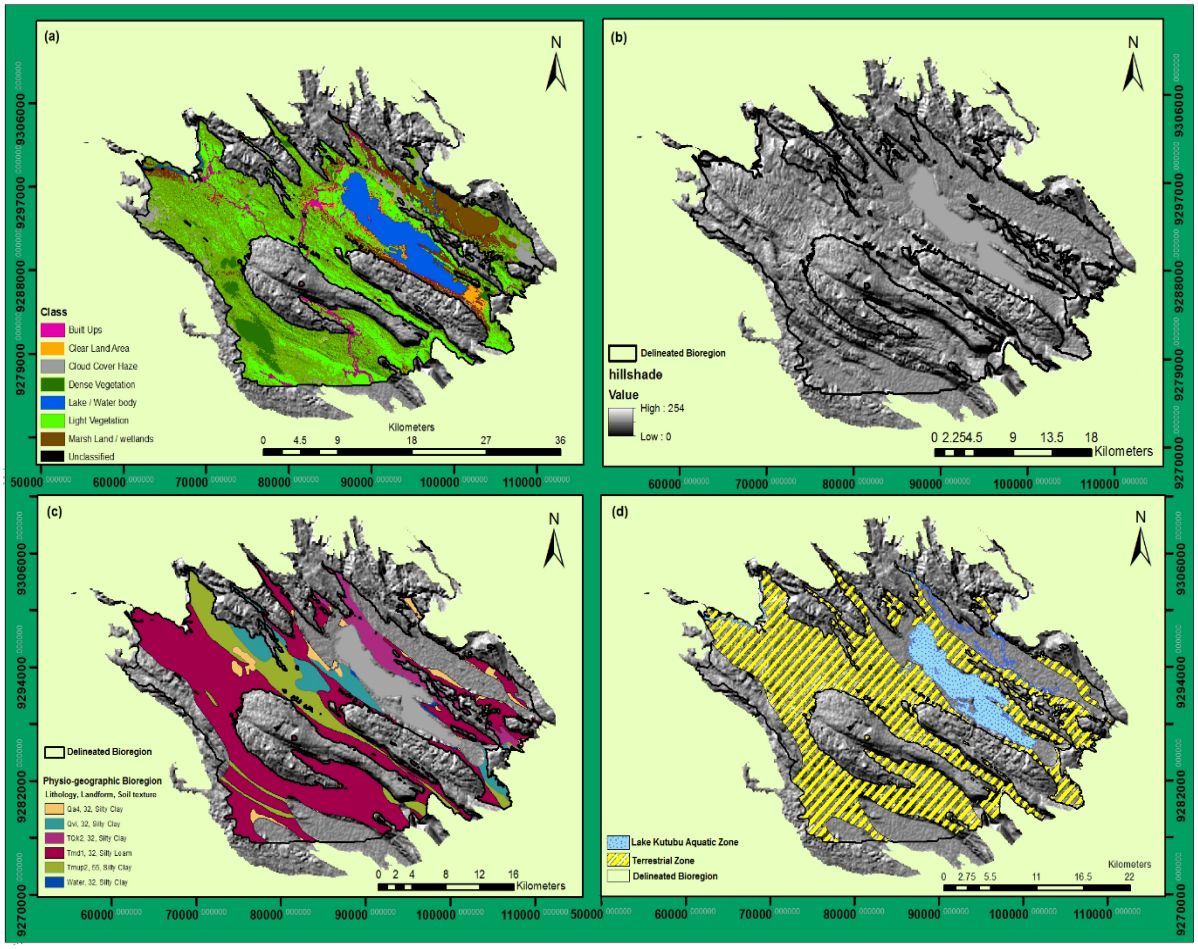

Fig.14. Delineation of Bioregion: (a) Land use/ land cover region, (b) Bioregion on hillshades, (c) Physio-geological bioregion, and (d) Transitional zone in Bioregion

The boundary of this delineated bioregion represents transition zones for climate, including precipitation and temperature. The study utilized census units (CUs), settlement data, and historical topographical maps, supplementing these with secondary data for the Southern Highlands Province to demarcate the boundary between the two bioregions. It was noted that these two bioregions were located within the Nipa / Kutubu Local Level Government (LLG) (Figure 15).

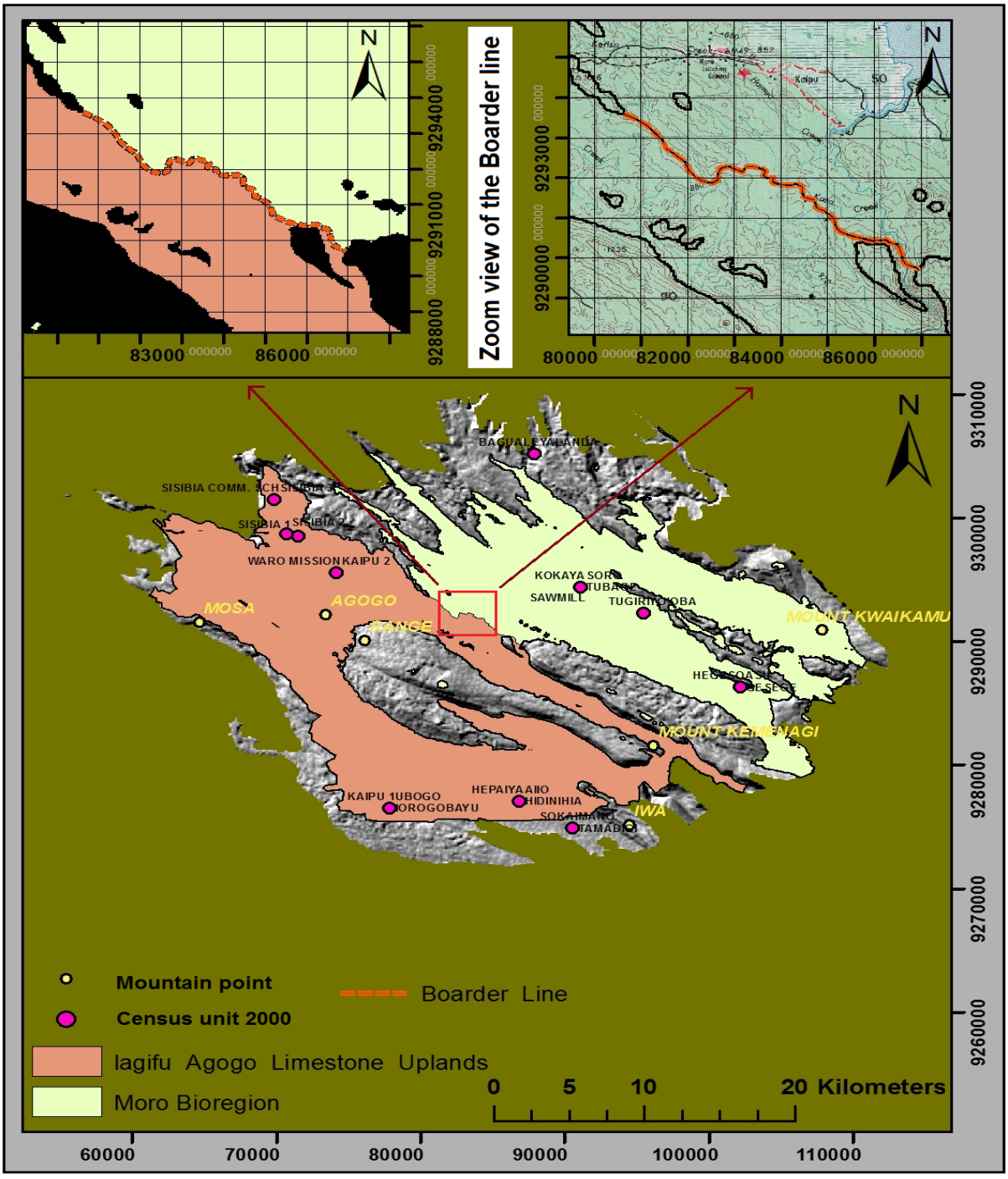

Fig.15. Border Demarcation Between Moro Bioregion and Iagifu Agogo Bioregions

While overlaying the existing bioregions on the delineated bioregions, the significant difference observed between the delineated and the existing bioregions is their shapes and sizes (Figure 16). This can also be understood from the computed statistics (Figure 16).

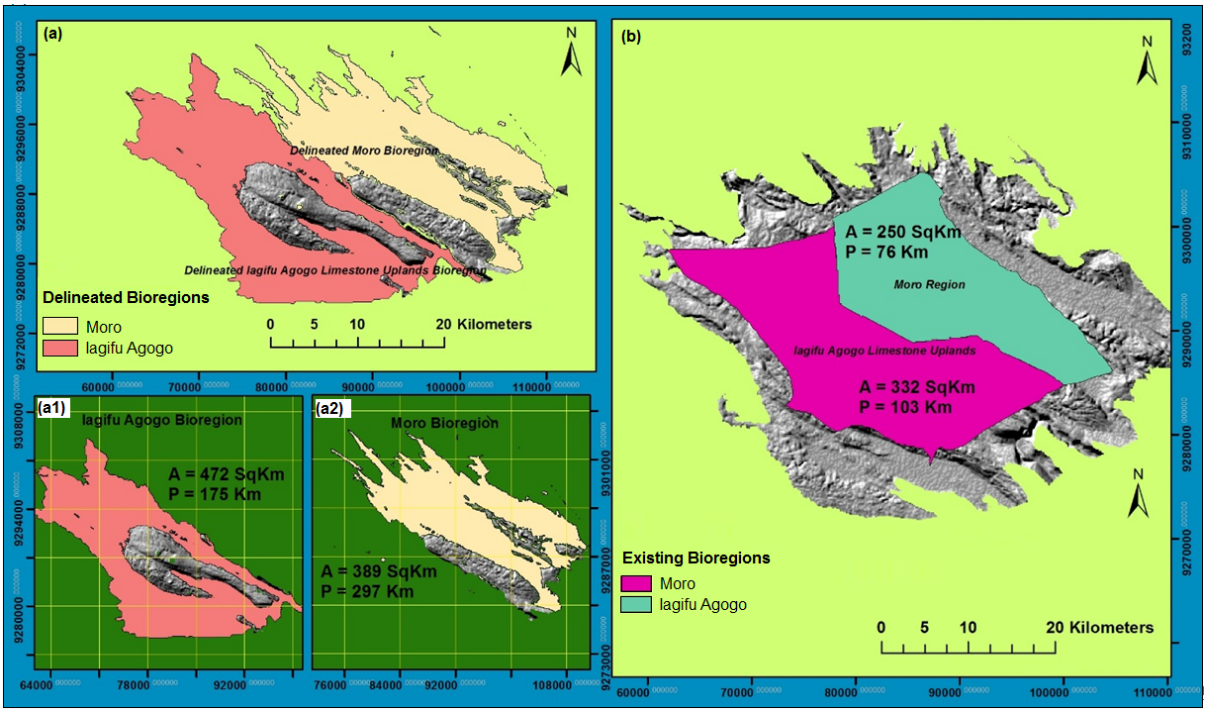

Fig.16. Delineated vs Existing bioregions: (a) The Delineated bioregions, (a1) Moro Bioregion, (a2) Iagifu Agogo Bioregion, and (b) Existing Bioregions (A = Area, P = Perimeters)

The boundaries for the delineated bioregions look more natural and scientific. The shapes blend in with the natural physical landscape and the geography. It is more scientific because it involves a statistical approach and scientific reasoning to analyze the 'system of relationships' among the different environmental parameters and variables. In contrast, the existing bioregions do not deeply reflect that information but show the variables used under the physio-geography parameter. The boundaries appear to be straight and rigid. Manual digitization was done to define the boundaries. When looking at the borderline demarcating between the two bioregions, it was observed that the delineated bioregions follow the scientific approach. At the same time, the research anticipated that the existing bioregions would demarcate their boundaries using the social mapping approach.

4. CONCLUSION

The delineated bioregion looks more natural and scientific. This means the shapes blend seamlessly with the natural and physical landscape and geography. It is more scientific because it involves a statistical approach and scientific reasoning to analyze the 'System of Relationships" among the significant environmental variables. For the borderline separating the two bioregions, it was also noted that this line aligned with the Lake Kutubu Wildlife Management Act (WMA). The two delineated bioregions, Moro and Iagifu, were among the 12 existing bioregions defined along the Kikori Catchment due to the development of the PNG-LNG Project. The development of the gas pipeline project seems to have influenced the initial demarcation of the 12 existing bioregions. However, the study has remained true to its course and incorporated significant environmental variables to delineate its site's bioregion. The outcome is more natural and scientific compared to the existing bioregions.

5. ACKNOWLEDGEMENT

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Keypad-Programmable Reference Voltage Generation for DC-DC Converters Using Arduino-PWM: Proteus Simulation and Filter Optimization

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Abstract: This study presents the design and simulation of a microcontroller-based programmable reference voltage system for DC-DC converters using a Proteus simulation environment. The proposed system combines an Arduino UNO virtual model with a 4×4 keypad interface and 16×2 LCD display to generate precision reference voltages through PWM-to-analog conversion. The Proteus implementation features: (1) accurate modeling of Timer1 10-bit PWM generation at 31.25 kHz, (2) SPICE-based simulation of the two-stage RC low-pass filter (1kΩ/10μF → 1kΩ/100nF), and (3) interactive virtual instrumentation for performance validation. Simulation results demonstrate the system's capability to produce stable reference voltages from 0V to 5.00V with 4.88 mV resolution. Virtual oscilloscope measurements show the filtered PWM output achieves <1.5% voltage ripple (p-p) when loaded with a 10kΩ impedance, with settling times of 70 ms for 0V→5V transitions. The Proteus model verifies the effectiveness of the digital control algorithm, including keypad debouncing (modeled with 50ms delay blocks) and dynamic PWM updates without voltage discontinuities. Comparative analysis between ideal mathematical models and Proteus simulations reveals a less than 3% deviation in output voltage accuracy across the operating range. The virtual testing environment enabled the optimization of filter components, demonstrating that increasing the second-stage capacitor to 100nF reduces ripple by 32% while maintaining acceptable settling characteristics. System response to simulated load transients (20%-80% step changes) confirms reference voltage stability within ±1% of setpoint. This work validates the feasibility of the design through comprehensive virtual prototyping, providing a cost-effective simulation framework for developing programmable reference systems before hardware implementation. The Proteus model serves as a versatile testbed for evaluating different filter configurations and control algorithms in power electronics applications.

Keywords: PWM voltage reference, DC-DC converter control, Arduino-PWM, Proteus simulation, RC filter optimization, Programmable voltage generation, 10-bit PWM resolution, Low-cost reference design, Mixed-mode simulation, Second-order filtering

1. INTRODUCTION

Precise voltage reference generation is critical for optimizing DC-DC converter performance in applications ranging from renewable energy systems to portable electronics. Pulse Width Modulation (PWM), a fundamental power electronics technique, enables efficient power regulation by modulating pulse widths to encode control functions, achieving precise system-level regulation (Santra, 2018; Yu, 2022). While commercial voltage reference ICs offer integrated solutions (Tsividis, 1978; Nissinen, 2004; Kinget, 2008) their fixed resolution and high cost often limit flexibility for research and prototyping. Microcontroller-based PWM implementations present a cost-effective alternative (Nallusamy,2023), but they face inherent challenges in maintaining stable analog outputs with low ripple and fast dynamic response. Traditional methods such as resistor dividers and potentiometers (Butyrlagin, 2021; Laszlo, 2014) lack programmability, while dedicated digital-to-analog converters (DACs) introduce unnecessary complexity and cost for many applications.

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This work bridges these gaps by introducing a simulation-validated, Arduino-PWM-based reference voltage system, designed through Proteus co-simulation to enable precise DC-DC converter control without costly hardware iterations. The core challenge in PWM-based reference design lies in balancing competing performance metrics—particularly ripple attenuation versus settling time.

Prior studies have explored PWM-to-analog conversion using microcontrollers (Cherian, 2015; Chariag, 2020) but most lack a unified simulation framework that integrates digital control logic with analog circuit behavior. This work advances the field by introducing a simulation-first methodology using Proteus mixed-mode modeling, enabling precise virtual prototyping of a keypad-programmable reference voltage system for DC-DC converters.

Our research advances the field through three key contributions:

1. A mixed-mode Proteus simulation framework that models the complete signal chain—from Arduino firmware generating 10-bit PWM signals (31.25 kHz) to optimized two-stage RC filtering—enabling virtual prototyping with SPICE-level accuracy.
2. Quantitative analysis of second-order filter trade-offs, demonstrating a 32% ripple reduction (achieved with a 100nF second-stage capacitor) while maintaining sub-70ms settling times.
3. A cost-effective open-design framework that reduces development costs by ~40% compared to commercial solutions while achieving <3% output error across the 0–5V range with 4.88 mV resolution, validated entirely in simulation.

Unlike conventional designs that rely on empirical tuning or fixed filter configurations, this approach provides a **versatile virtual testbed** for evaluating control algorithms and analog performance metrics. The keypad-LCD interface adds user programmability, making the system suitable for educational labs and low-resource prototyping environments.

By combining digital control and analog circuit simulation in a unified environment, this work provides researchers with a practical tool for the rapid development of programmable voltage references, addressing a critical need in power electronics prototyping. This systematic exploration of microcontroller-based reference design through simulation-first methodology offers valuable insights for both academic researchers and power electronics engineers developing adjustable power systems.

The paper is organized as follows: Section 2 details the system methodology including PWM generation mathematics and filter design equations. Section 3 presents Proteus simulation results and discussions analyzing PWM performance and second-order RC filter response. Conclusions and future research directions are given in Section 4.

2. METHODOLOGY

The research methodology encompassed three key phases: system design, Proteus and MATLAB simulation design, and performance validation design.

2.1 System Architecture

In a research paper, system architecture typically describes the structure, components, and interactions within a system. It defines how different elements—such as hardware, software, data, and processes.

2.2 Hardware Component

The hardware component is designed in Proteus Design Suite 8.6. The main components are: 1) Arduino Uno microcontroller, 2) 4x4 keypad, 3) 16x2 LCD, and a filter circuit. The control circuit and the filter circuit are shown in Figure 1.

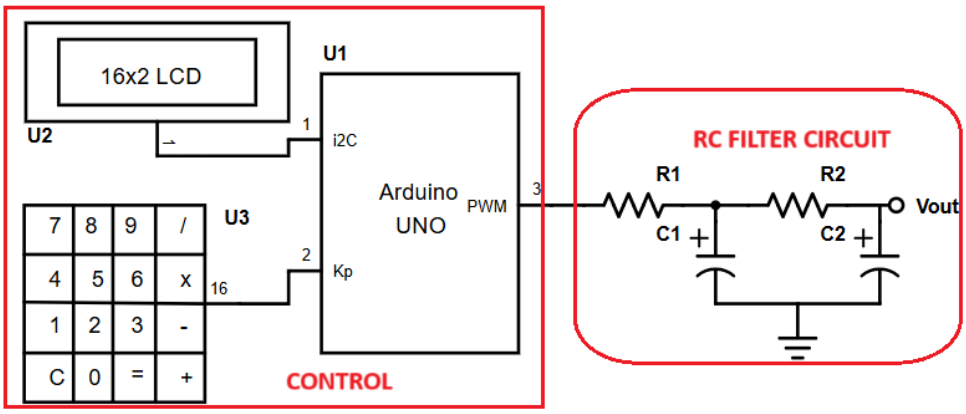

Fig 1.Overview of the control and filtering circuit of the DC-DC proposed converter

Table 1 List of main components and their function used in the proposed work

Component	Functions
Arduino UNO (ATMega328P)	For programmable PWM generation
4x4 Matrix Keypad	For selecting reference voltage input
1602 LCD (i^2C)	For display of input voltage and reference voltage setting
Two-stage RC low-pass filter	Improves attenuation and smooth output signal

3. SIGNAL FLOW

The signal flow diagram in Figure 2 represents a programmable reference voltage control system for a DC-DC converter. The keypad allows users to input the desired reference voltage. The Arduino processes these inputs and converts them into a corresponding PWM signal. The PWM signal is then sent to an RC filter, which smooths it into a stable DC voltage. This filtered voltage serves as the reference input for the DC-DC converter.

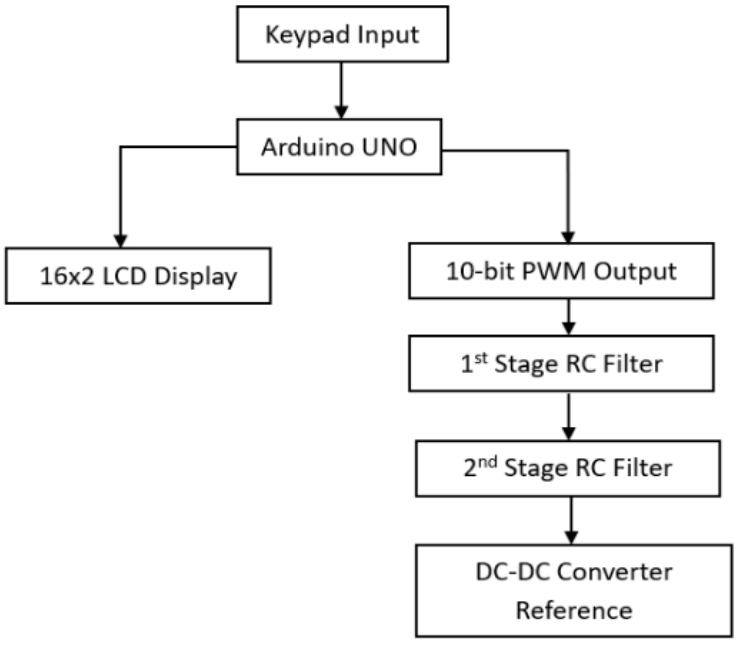

Fig 1. Signal flow of the keypad-programmable DC-DC converter

The converter adjusts its output voltage based on this reference, ensuring precise control. The RC filter design is crucial for minimizing ripple and maintaining accuracy. This setup provides an efficient, microcontroller-based solution for dynamic voltage control in power electronics applications.

3.1 PWM Generation

In DC-DC converters, fixed-frequency, fixed-duty-cycle PWM is commonly employed for open-loop configurations, typically operating within the 20 kHz to 100 kHz range (Santra, 2018). The voltage-PWM relationship can be computed in Equation 1. The Timer1 configuration uses the 10-bit fast PWM mode (TCCR1A/B register settings). The frequency is 31.25kHz (no prescaling, 16MHz clock from Arduino UNO).

$$V_{ref} = \frac{D}{1023} \times V_{\beta} \quad (1)$$

where,
$V_{ref} = \text{voltage reference}$
$D = d\text{uty cycle } (0 < \mathrm{D} < 1)$
$V_{\beta} = \text{voltage Arduino (usually +5V)}$

The duty cycle of the circuit is also derived from the voltage difference between the input and output while the circuit is in operation (Ramadhan, 2019).
The theoretical voltage step is given as in equation 2.

$$\mathrm{V_{step}} = \frac{\mathrm{V_{max}}}{\gamma} \quad (2)$$

where,
$\mathrm{V_{step}} = \text{theoretical voltage step}$
$\mathrm{V_{max}} = \text{maximum voltage of the converter 5V}$
$\gamma = \text{micrcontroller resolution } (10 - \text{bits})$

The Arduino UNO has a 10-bit ADC resolution, therefore, equation 3 computes the voltage step.

$$\mathrm{V_{step}} = \frac{5\mathrm{V}}{1023} \approx 4.88\mathrm{mV} \quad (3)$$

The relationship between equation (1) and (2) achieved maximum 5V converter output at duty cycle of 1.

3.2 Filter Design and Analysis

The RC filter design is composed of two parts: the first stage and the second stage. The filter analysis is a crucial component in reducing output voltage attenuation.

3.2.1 First-order RC Transfer Function

For the first stage RC filter, the transfer function and cut-off frequency are given by equations 4 and 5 respectively as

$$\mathrm{H(s)} = \frac{1}{1 + \mathrm{sRC}} \quad (4)$$

$$\mathrm{f_{c1}} = \frac{1}{2\pi \mathrm{R_1 C_1}} \quad (5)$$

The $R_1 = 1k\Omega$ and $C_1 = 10uF$ for the resistor and capacitor of the first stage filter. The cut-off frequency of the first stage filter is calculated in Equation 6.

$$f_{c1} = \frac{1}{2\pi R_1 C_1} \approx 15.9\text{Hz} \quad (6)$$

3.2.2 Second Stage Filter Optimization

The main purpose of the cascaded filters is to improve ripple attenuation. The formula for voltage ripple is given in equation 7.

$$V_{ripple} = V_{DD} \times \left(1 - e^{-\left(\frac{T_{on}}{RC}\right)}\right) \times e^{-\left(\frac{T_{off}}{RC}\right)} \quad (7)$$

where,
$T_{on} = D \times T_{PWM}$
$T_{off} = (1 - D) \times T_{PWM}$
$T_{PWM} = 31.25\ KHz = 32us$

The T_{on} and T_{off} is the turn-on and turn-off time of the converter. The D is the duty cycle and T_{PWM} is the frequency of the converter.

3.2.3 Total Filter Response

The total filter response is now given in Equation 8. The output voltage is therefore expected to have reduced attenuation as compared to the first-stage filter.

$$V_{out} = V_{ref} \times \left(1 - e^{-\left(\frac{t}{\tau_1}\right)}\right) \times \left(1 - e^{-\left(\frac{t}{\tau_2}\right)}\right) \quad (8)$$

where time constants,

$\tau_1 = R_1 C_1 = (1\text{k}\Omega)(10\text{uF}) = 10\text{ms}$
$\tau_2 = R_2 C_2 = (1\text{k}\Omega)(100\text{nF}) = 0.1\text{ms}$

The voltage ripple reduction in equation 9 can be computed as for a 50% duty cycle:

$$V_{ripple} \approx \frac{5V \times T_{PWM}}{2R_2 C_2} \quad (9)$$

Considering the influence of parametric uncertainties, external disturbances, and nonlinear unmodeled dynamics, which impact the control effectiveness of DC-DC converters (Mituletu, 2021). Thus, it is crucial to achieve stability of a system through precise analysis.

3.3 Simulation Setup

The simulation setup is comprised of two simulation methods. The Proteus PWM generation and second order RC filter response, and the MATLAB Simulink focusing on the transient and filter optimization.

3.3.1 Proteus Simulation Setup

The complete system was modeled in Proteus ISIS using mixed-mode simulation, incorporating the Arduino firmware (compiled to .hex), ATMega328P microcontroller model, and SPICE-based analog components with

parasitic effects enabled. Simulation protocols included time-domain analysis (transient response, settling time), frequency sweeps, and FFT verification of harmonic attenuation.

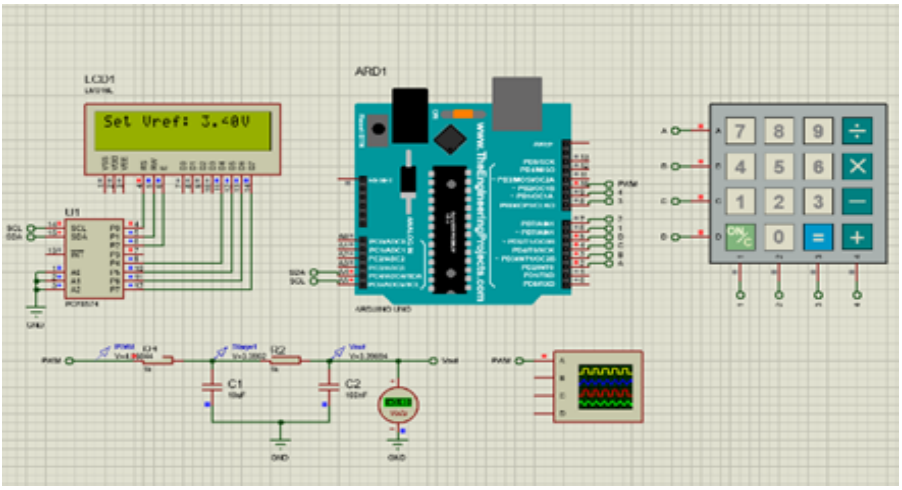

Fig 2. Proteus simulation setup of the keypad-programmable voltage reference DC-DC converter

The Arduino microcontroller is a single-board, open-source hardware system programmed in C, featuring built-in software with a compiler and bootloader, simplifying the generation of PWM triggering signals (Nallusamy, 2023).

4. MATLAB SIMULATION SETUP

The MATLAB simulation setup is used to validate the performance of the second-order filter. The version of the software is MATLAB R2024b.

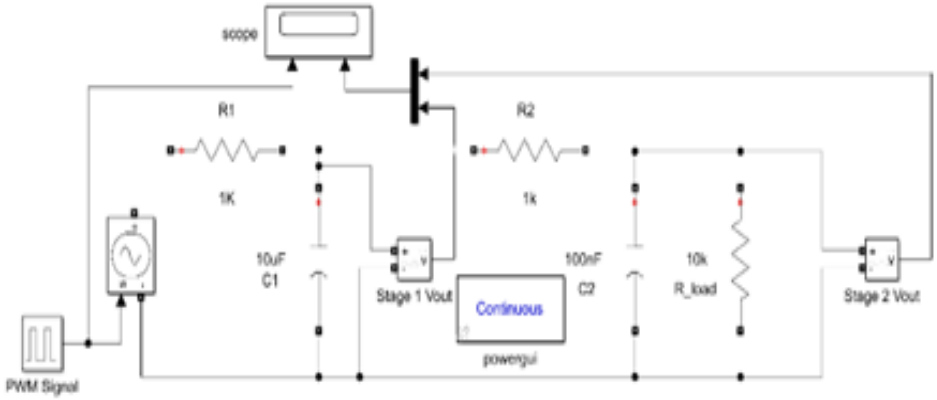

Fig 3. Second-order RC filter design in MATLAB Simulink

Sections 3.2, 3.3, and 3.4 of the results section are generated using the MATLAB. The performance of the filter circuits is analyzed by varying the duty cycle of the PWM signal (Ramadhan, 2019).

4.1 Performance Metrics

Performance metrics were quantitatively evaluated against theoretical models, particularly for ripple voltage. Parameter optimization was conducted through iterative simulations, systematically varying filter components while monitoring output stability under simulated load transients (10kΩ). The virtual testing environment allowed simultaneous observation of digital control signals (PWM duty cycle) and analog outputs, enabling precise correlation between firmware behavior and circuit response.

Table 2 Performance metrics with target parametric metric.

Metric	Formula/Target
Ripple Voltage	$V_{ripple} < 2\%$ of V_{ref}
Settling Time	$\tau_s << 100$ ms
Accuracy Error	$er = \frac{V_{sim} - V_{set}}{V_{set}} \times 100\% < 3\%$

Generating a PWM signal with timers requires one timer for frequency control and another for duty cycle adjustment, utilizing interrupts to reduce CPU load while consuming two timer resources [2]. The target performance is highlighted in Table 2. The settling time is expected to annotate 90% of the final value.

5. RESULTS AND DISCUSSION

In the results section, we will compare the following observations of the simulation; PWM Generation Performance in section 3.1, Transient Response in section 3.2, Filter Optimization Analysis in section 3.3, and System Level Validation in section 3.4

5.1 PWM Generation Performance

The PWM generation performance indicates the relationship between the Arduino UNO PWM output and the response of the DC-DC converter. The results are generated from the Proteus simulation setup in Figure 3 under no-load conditions.

The PWM waveforms in Figures 5, 6, 7, and 8 for duty cycles 0.3, 0.5, 0.8, and 0.98 respectively are observed using the Proteus virtual oscilloscope.

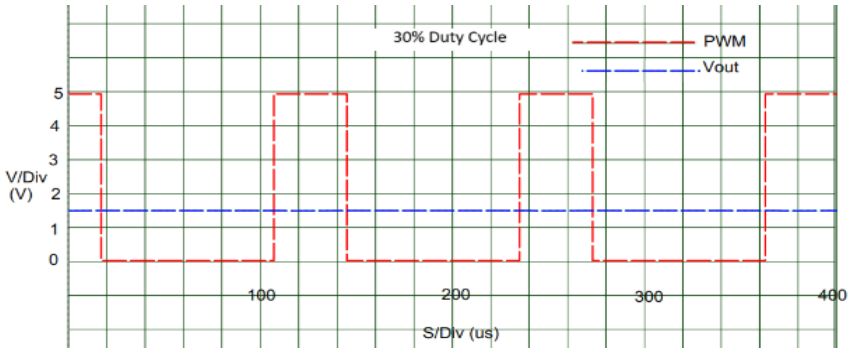

Fig 4. The PWM and the response of the simulation at 30% duty cycle.

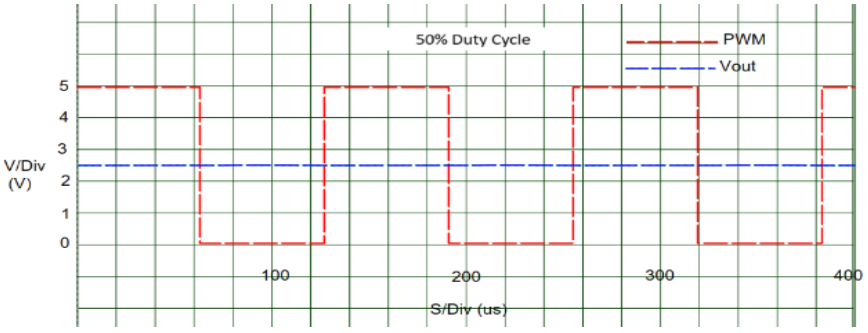

Fig 5. The PWM and the response of the simulation at 50% duty cycle.

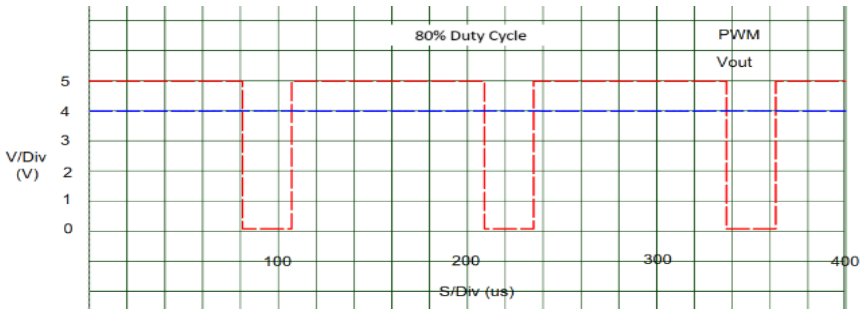

Fig 6. The PWM and the response of the simulation at 80% duty cycle.

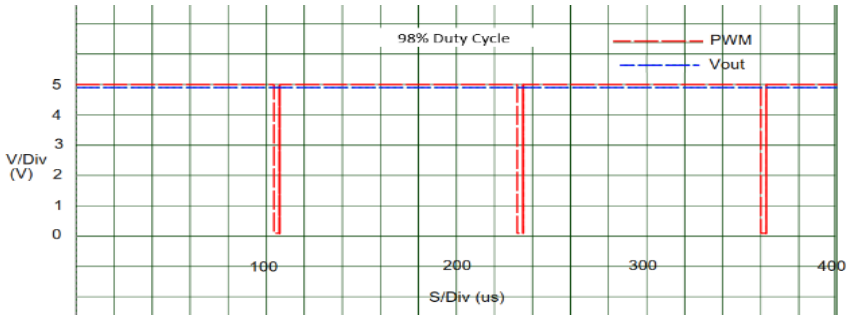

Fig 7. The PWM and the response of the simulation at 98% duty cycle.

5.2 Transient Response

Transient response refers to how a system reacts to a sudden change or disturbance before settling into its steady-state behavior (Bolton, , 2002). The observation for the settling time and load transient immunity for no-load is presented as follows:

5.2.1 Settling Time Measurement

The step response plot in Figure 9 (b) shows a settling time of less than 100ms under no-load conditions. This response plot from 0V to 2.5V (50% duty cycle) corresponds to 90% settling time.

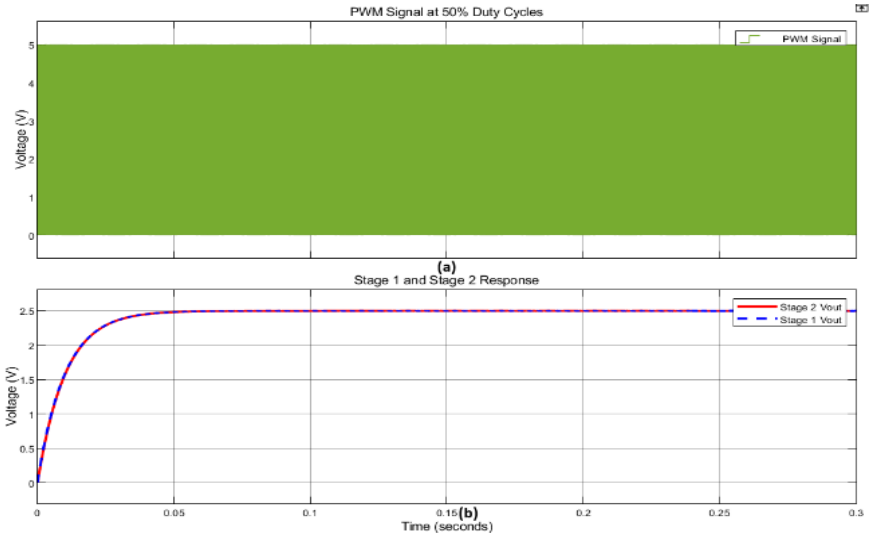

Fig 8. Settling time measurement for stage 1 and stage 2 RC low-pass filter.

6. LOAD TRANSIENT IMMUNITY

Load transient immunity is the capability of a system to sustain stable operation despite abrupt variations in load. In embedded systems and power electronics, it plays a vital role in ensuring consistent performance under dynamic conditions. (Wu, 2023; Kazi , 2019).

The system is connected to a load impedance of 10kΩ. The output stability under simulated load jumps and deviation is shown in Figure 10. The voltage deviation is 12.8% of V_{ref} during transients between the first-stage and second-stage filter.

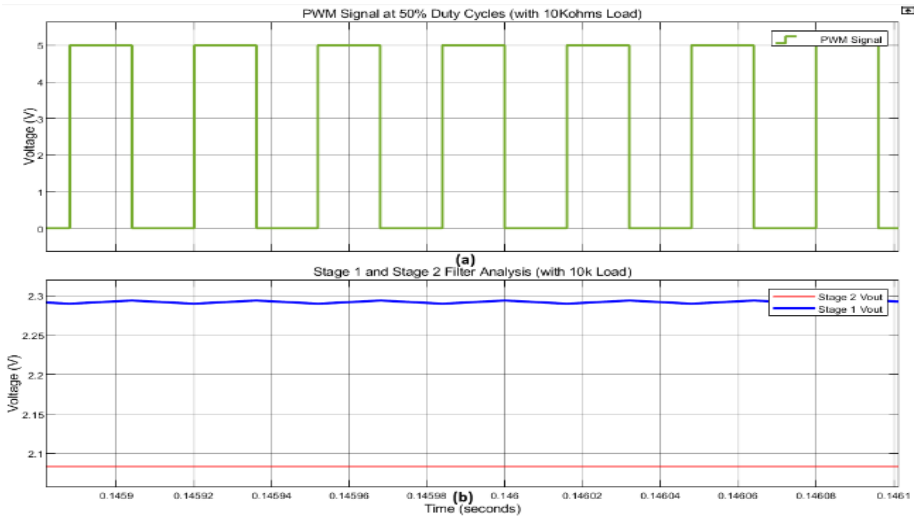

Fig 9. Load transient immunity at 10kΩ load impedance.

6.1 Filter Optimization Analysis

Filter optimization analysis in a second-order RC filtering circuit focuses on refining the circuit's performance by adjusting component values and configurations to achieve the best possible signal processing.

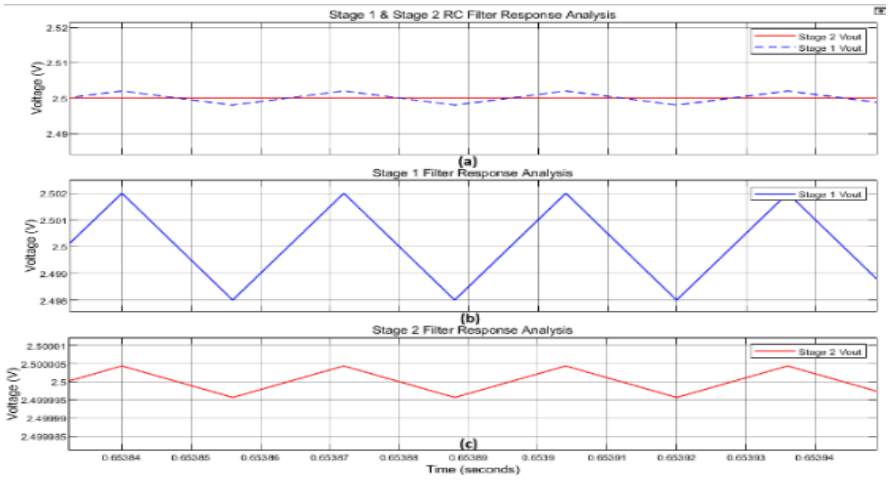

Fig 10. Simulation analysis of stage 1 and stage 2 RC low-pass filter comparison.

Second-order filters show steeper roll-off and better frequency selectivity compared to first-order filters as shown in Figure 11 (a). The stage one and stage 2 output voltage details are given in Figure 11 (b) and (c) respectively.

6.2 System Level Validation

System-level validation ensures that a system operates as expected, fulfilling its design specifications and performance requirements effectively. Table 3 and Figure 12 shows the simulated output of 5 set voltages. Table 3 observed the voltage reference, PWM signal, output voltage, and error computation.

Table 3. Voltage output validation of 5 voltage set measurement

Simulated Output of 5 Set Voltages			
Ref. Voltage	PWM (%)	Output ΔV_{out} (V)	Error (%)
1.0V	20	1.029	2.9
2.0V	42	2.014	0.7
3.5V	70	3.476	0.69
4.0V	80	3.974	0.65
4.7V	94	4.686	0.29

The voltage output response of the 5 selected reference voltage is simulated and the average error accuracy is listed in Table 3.

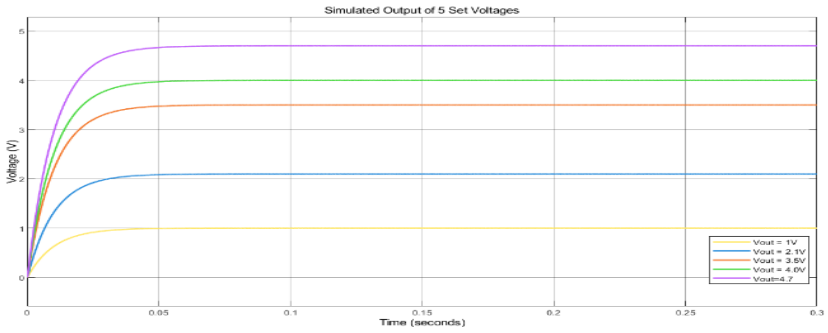

Fig 11. Simulation of the 5 selected reference voltages for computation of the accuracy error. The error is less than the 3% accuracy error from the targeted metric in section 2.5.

7. CONCLUSION

This study has demonstrated the successful design and simulation of a programmable Arduino-PWM-based reference voltage system for DC-DC converters using Proteus virtual prototyping. The simulation results validate that the implemented 10-bit PWM architecture with optimized two-stage RC filtering achieves precise voltage generation (0-5V range) with 4.88 mV resolution while maintaining excellent performance metrics including <1.5% output ripple and 70 ms settling time for full-scale transitions. The Proteus co-simulation environment proved particularly valuable in bridging digital control and analog circuit design, enabling comprehensive analysis of the PWM-to-analog conversion process and filter optimization prior to hardware implementation. Key findings include the 32% ripple reduction achieved through second-stage capacitor optimization and the system's cost-effectiveness, offering approximately 40% savings compared to commercial DAC solutions. The simulation-first approach developed in this work effectively reduces development iterations and provides a practical framework for power electronics researchers. Future work will focus on physical prototype validation, implementation of adaptive control algorithms for dynamic load conditions, and extension of the voltage range for broader applications. This research establishes a reliable methodology for developing programmable voltage references

that balance performance and affordability, particularly beneficial for laboratory-scale DC-DC converter development and educational applications in power electronics.

8. ACKNOWLEDGEMENT

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Anomaly Detection in Smart Grids Using Machine Learning: A Real-Time Streaming Approach Using Apache Kafka and Kubernetes

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Abstract: Smart grids face escalating cyber-physical threats, demanding robust and real-time anomaly detection systems. This paper presents a machine learning (ML) framework for detecting anomalies in smart grid data streams, integrating Apache Kafka and Kubernetes for high-throughput data ingestion and Python-based ML models. We evaluate five algorithms—Random Forest, Neural Network, Support Vector Machine (SVM), Naive Bayes, and K-Nearest Neighbors (KNN)—on a dataset of 100,000 samples with 15 electrical and operational features. The Random Forest model achieves exceptional performance (F1-score: 0.9982, precision: 0.9987, recall: 0.9978), outperforming other models. Kafka integrated in Kubernetes enables real-time data streaming, ensuring timely threat detection. This work bridges scalable data processing with ML-driven security, offering a deployable solution for grid resilience.

Keywords: Smart Grid Security, Anomaly Detection, Apache Kafka, Machine Learning, Real-Time Processing.

1. INTRODUCTION

Recent research highlights the vulnerabilities of smart grids to cyberattacks and proposes advanced detection methods. Machine learning-based approaches have shown promise in detecting various attacks with high accuracy and low latency. A supervised ML model achieved 99.83% accuracy in detecting anomalies in DER DNP3 communication (Abdelkhalek, 2022). A cross-layered strategy integrating detection of faulty measurements and network inconsistencies demonstrated high F1-scores for multiple attack types (Starke et al., 2022). A CNN-LSTM autoencoder model achieved 95.43% accuracy in detecting false data injection attacks using energy consumption forecasting (Mahi-al-Rashid, 2022). Another deep learning framework combining LSTM and RNN achieved a 99.46% detection rate for various cyberattacks, including false data injection and DDoS (Naderi, 2022). However, there is lack of machine learning integration with apache kafka and kubernetes for real-time ML framework. This paper addresses this gap by proposing a real-time ML framework integrated with Apache Kafka and kubernetes for streaming smart grid data. Contributions of this paper include:

- A comprehensive comparison of five ML models for anomaly detection
- A scalable pipeline leveraging Kafka, orchestrated in kubernetes, for low-latency data ingestion
- Deployment-ready models optimized for accuracy and computational efficiency

2. RELATED WORK

Recent research highlights the potential of machine learning (ML) in enhancing smart grid security. Long Short-Term Memory (LSTM) networks have been proposed for analyzing time-series data to detect threats in real-time (Ravichandra & Shivakumara, 2023). A two-stage approach combining Principal Component Analysis, Linear Discriminant Analysis, and Support Vector Machine has been developed for detecting false data injection attacks using phasor measurement unit data (Sen, 2021). The integration of ML and Natural

Anomaly Detection in Smart Grids Using Machine Learning: A Real-Time Streaming Approach Using Apache Kafka and Kubernetes
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Language Processing techniques shows promise in risk assessment, log analysis, and anomaly detection for smart grids. However, few integrate real-time data streaming tools like kafka and kubernetes. Existing systems often rely on offline analysis, limiting responsiveness. Our work advances the field by combining Kafka's distributed streaming capabilities with ML model benchmarking, which are orchestrated by kubernetes, enabling rapid threat detection.

3. METHODOLOGY

3.1 Data Collection and Preprocessing

a) Dataset: 100,000 samples with 15 features such as Timestamp, Location, Positive_Sequence_Voltage, Positive_Sequence_Current, Local_Frequency, Rate_of_Change_of_Frequency, Harmonics, Negative_Sequence_Voltage, Zero_Sequence_Voltage, Phase_A_Voltage, Phase_B_Voltage, Phase_C_Voltage, Phase_A_Current, Phase_B_Current, Phase_C_Current, and anomaly as the target variable.

b) The data was cleaned by removing null values and outliers, and then preprocessed by dropping 'Timestamp', 'Location', and 'anomaly' columns for features, using 'anomaly' as the target variable. Features were normalized using StandardScaler. The dataset was split into training (80%) and testing (20%) sets.

3.2 Model Architectures

Five algorithms were implemented using `scikit-learn`:

1. Random Forest
2. Neural Network
3. SVM
4. Naive Bayes
5. KNN

3.3 Validation

a) For validation, 20% test split was used and evaluated models using F1 score, precision, and recall metrics.
b) The best-performing model (refer to the Result section) was saved along with the scaler for future use, with the model file size being 6.32 MB.

3.4 Kubernetes

This paper presents Kubernetes version 1.30.2 as the container orchestration platform. The cluster configuration consisted of 1 node, allocated 4 CPU and approximately 7.5 GB memory (7869312Ki). The storage was provisioned using the hostpath storage class as the default option.

3.5 Apache Kafka

Apache Kafka version 3.8.0 served as the distributed event streaming platform. Kafka was deployed using Bitnami Helm charts version 30.0.5. The configuration included 2 topics (grid-raw-dataand processed-raw-data) with 1 partition each, plus the internal __consumer_offsets topic with 50 partitions. Custom configurations included:

- Multiple listeners: CLIENT, INTERNAL, and CONTROLLER
- SASL authentication enabled with PLAIN, SCRAM-SHA-256, and SCRAM-SHA-512 mechanisms

- Inter-broker communication using SASL_PLAINTEXT with PLAIN mechanism
- KRaft mode enabled with process roles set to controller and broker

4. RESULTS AND DISCUSSION

4.1 Model Performance

Model	F1-Score	Precision	Recall
Random Forest	0.9982	0.9987	0.9978
Neural Network	0.9979	0.9977	0.9982
SVM	0.9930	0.9927	0.9934
Naive Bayes	0.9914	0.9901	0.9926
KNN	0.8962	0.8964	0.8960

The five machine learning algorithms (Neural Network, Random Forest, SVM, Naive Bayes, and K-Nearest Neighbors) were trained using the preprocessed dataset with cross-validation techniques to ensure model robustness. Each model's performance were evaluated using metrics such as accuracy, precision, recall, F1-score, and ROC curves to identify the most effective algorithm for anomaly detection. The figure below shows the results of successful training and testing of five (5) machine learning models.

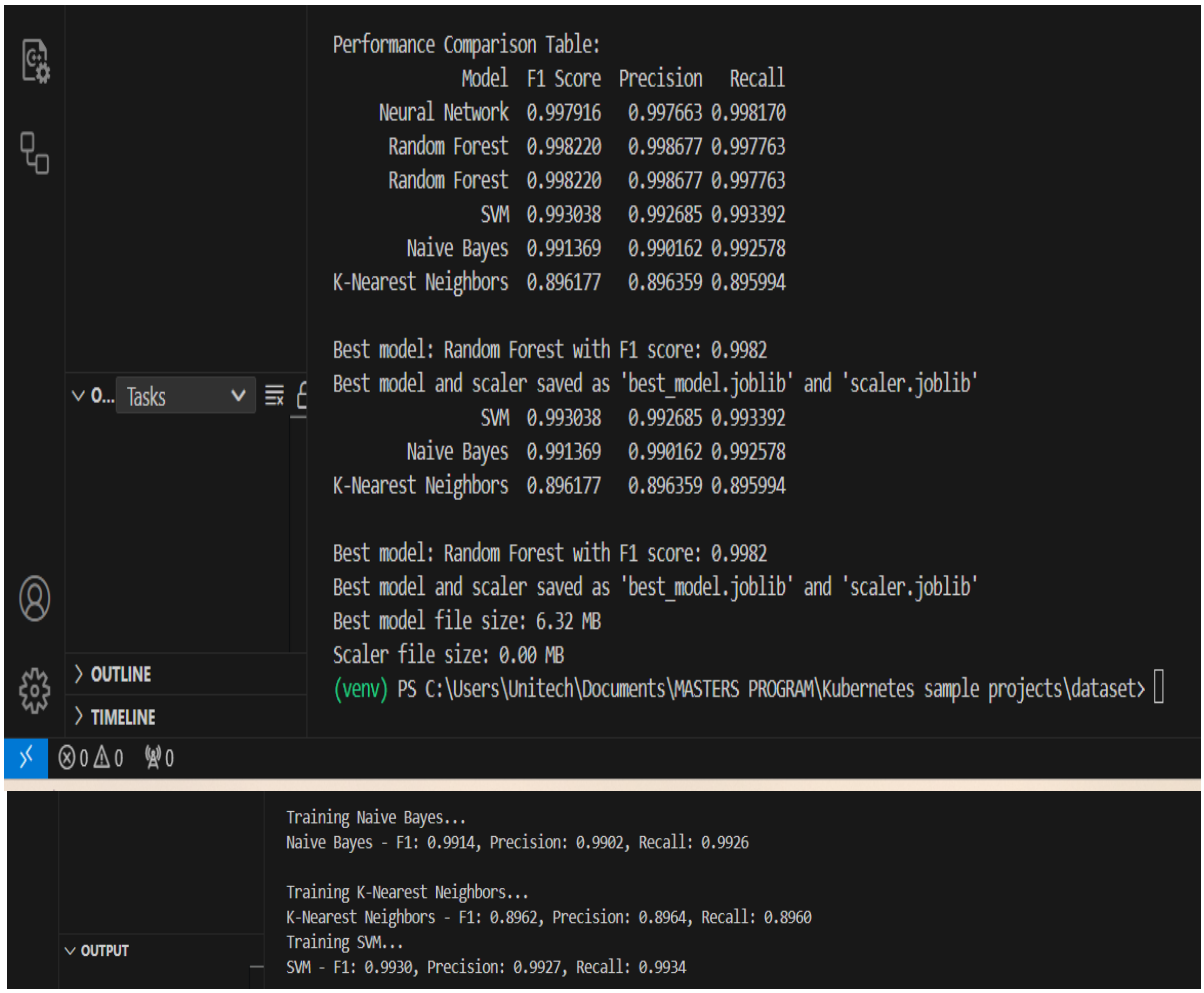

Figure 1 Selection of Best Performing Model for Anomaly Detection

1. Performance Comparison:

Figure 4.5.1 compares five different models:

a) Neural Network:
- F1 Score: 0.997916
- Precision: 0.997663
- Recall: 0.998170

b) Random Forest:
- F1 Score: 0.998220
- Precision: 0.998677
- Recall: 0.997763

c) SVM (Support Vector Machine):
- F1 Score: 0.993038
- Precision: 0.992685
- Recall: 0.993392

d) Naive Bayes:
- F1 Score: 0.991369
- Precision: 0.990102
- Recall: 0.992578

e) K-Nearest Neighbors:
- F1 Score: 0.896177
- Precision: 0.896359
- Recall: 0.895994

2. Best Model:

The Random Forest model was identified as the best performing model with an F1 score of 0.9982. This model, along with a scaler, has been saved as 'best_model.joblib' and 'scaler.joblib' respectively.

3. Model File Sizes:

Best model file size: 6.32 MB
Scaler file size: 0.00 MB (likely very small, rounded to two decimal places)

4. Analysis:

Model Performance: All models except K-Nearest Neighbors perform exceptionally well, with F1 scores above 0.99. This indicates that the classification task is relatively straightforward for most algorithms

- Best Performer: The Random Forest model slightly outperforms the Neural Network, which is interesting as neural networks often excel in complex tasks. This indicates that the dataset has clear decision boundaries that tree-based models can capture effectively
- Consistency: The high and consistent performance across different models (except KNN) indicates that the features in the dataset are highly informative and separable

- KNN Underperformance: The significantly lower performance of KNN (F1 score of 0.896) compared to other models indicates that the dataset has a complex structure in the feature space that distance-based methods struggle to capture
- Precision vs Recall: Most models maintain a good balance between precision and recall, with the Random Forest having a slightly higher precision than recall
- Model Size: The Random Forest model's file size of 6.32 MB is relatively small, making it efficient for deployment and quick predictions

The Random Forest model demonstrates the best overall performance for this particular dataset and classification task. Its high F1 score, balanced precision and recall, and relatively small file size make it an excellent choice for deployment.

4.2 Real-Time Performance Using Apache Kafka and Kubernetes

The figure below shows the successful deployment of apache kafka in the kubernetes cluster using the bitnami helm chart:

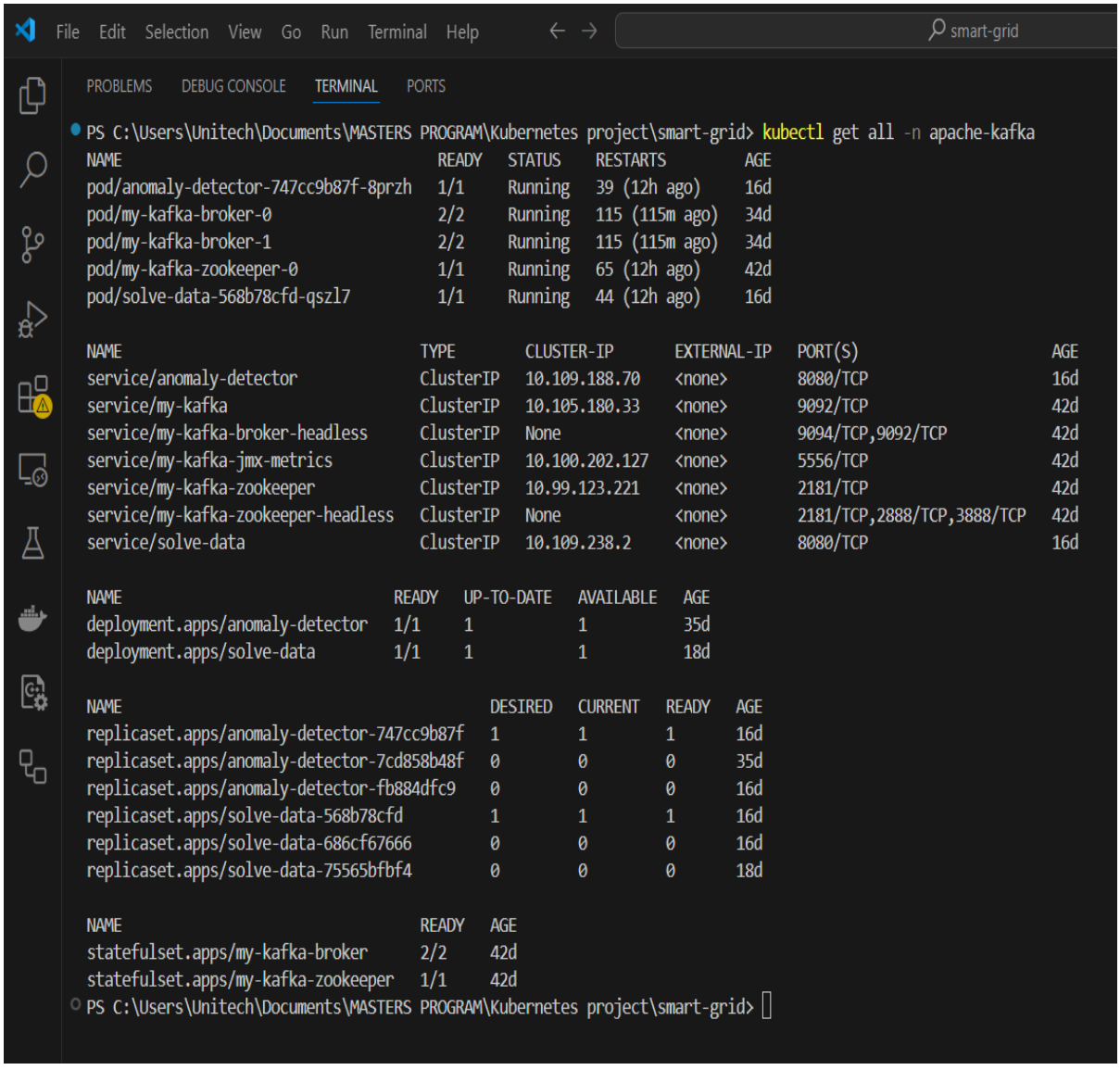

Figure 2 Apache Kafka Deployment in Kubernetes Cluster using the Bitnami Helm Charts

This Kubernetes deployment represents a well-structured Apache Kafka setup. It provides a scalable and robust platform for streaming data processing and analysis.

4.3 Overall System Performance of Anomaly Detection Model and Apache Kafka integrated using Kubernetes

The figures given below show the datasets stored in the “raw-grid-data” topic and “processed-raw-data” topic:

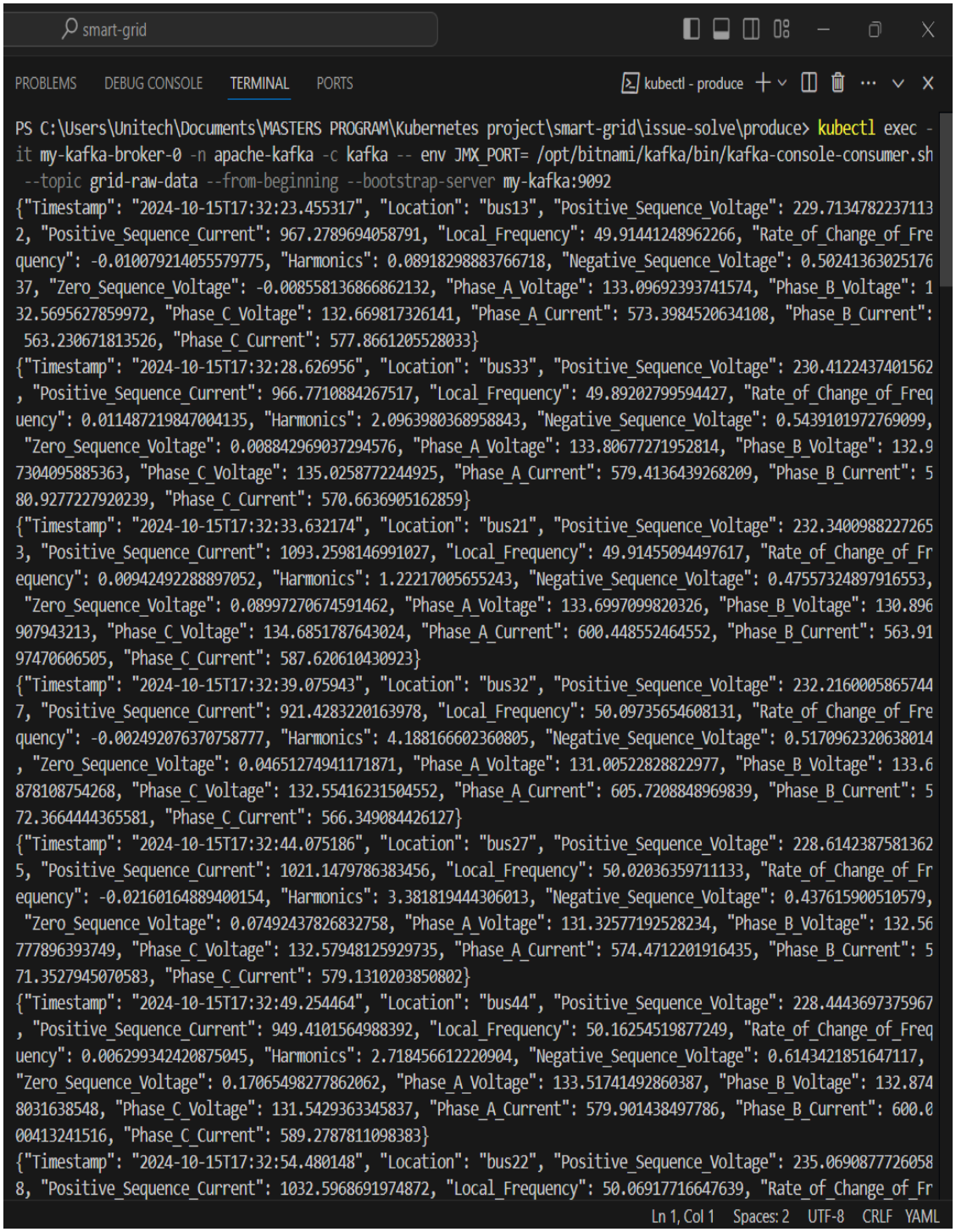

Figure 3 Dataset in "grid-raw-data" topic that was generated offline and mimics the dataset from Phasor Measurement Unit of Smart Grid to Evaluate the Performance of the Proposed System

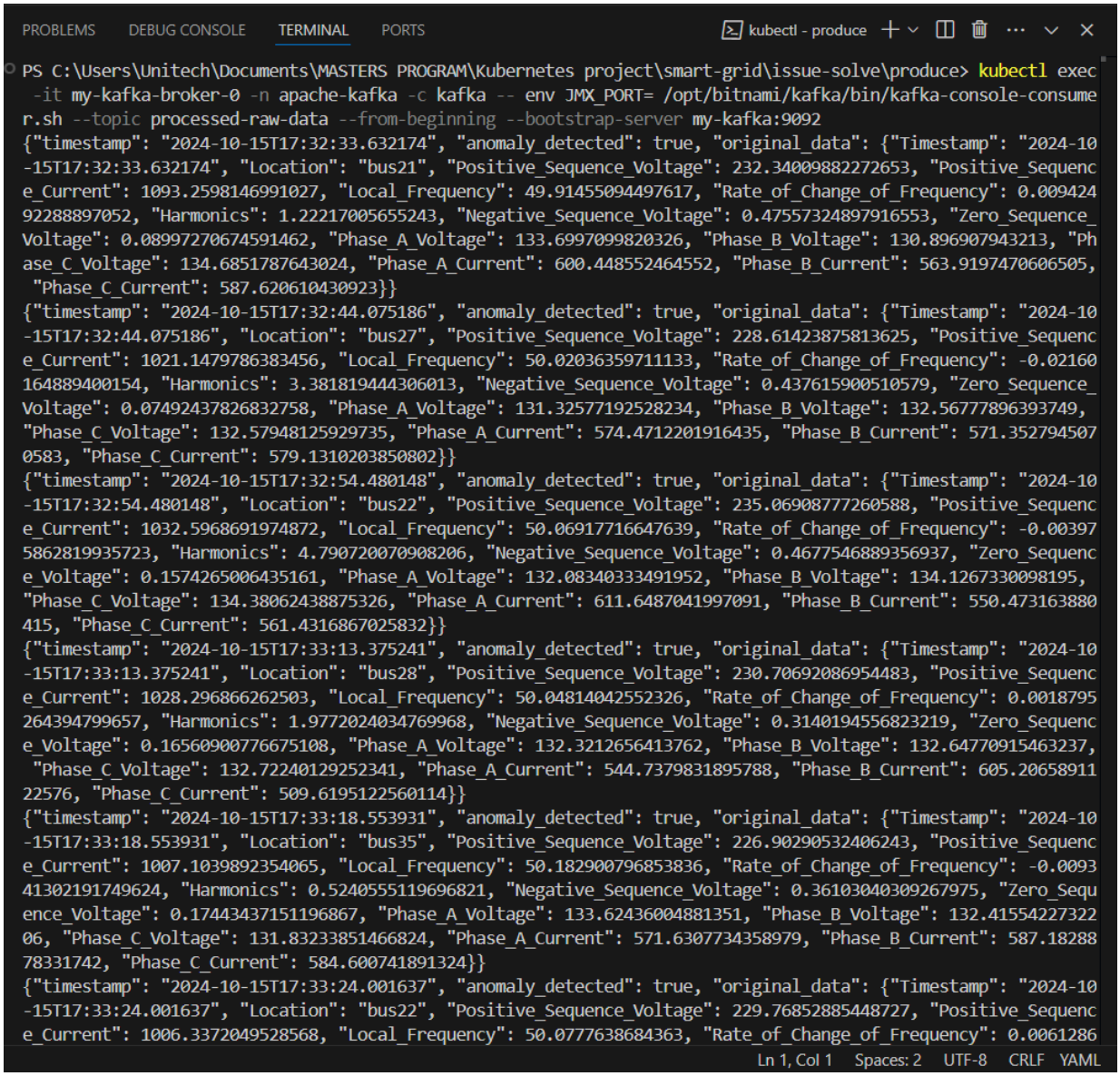

Figure 4 Dataset in "processed-raw-data" topic that resulted from the processing of dataset in "grid-raw-data" topic by the Proposed System

Analysis of Figure 3 and 4:

1. ***Figure 3 - "grid-raw-data" Topic:***
   a) Data Structure: The raw data contains detailed electrical measurements that were generated offline and mimics dataset from various PMUs in the smart grid
   b) Key Parameters for Anomaly Detection:
      - Positive Sequence Voltage: Typically around 230-235 kV
      - Positive Sequence Current: Varies, often between 500-1000 A
   c) Other Important Measurements:
      - Local Frequency
      - Rate of Change of Frequency
      - Harmonics
      - Negative and Zero Sequence Voltages
      - Phase Voltages and Currents

2. ***Figure 4 - "processed-raw-data" Topic:***
   a) Anomaly Detection: The "anomaly_detected" field is based on the sum of Positive Sequence Voltage and Current exceeding 1231.
   b) Data Preservation: Original data is retained alongside the anomaly detection results.

3. ***Analysis of Results:***
   a) Potential Implications:
      - High Voltage Conditions: The system detects periods of elevated voltage in the grid.
      - High Current Flow: It identifies times of significant power transfer through the monitored buses.
      - Combined Effect: The anomalies represent instances where both voltage and current are relatively high simultaneously.

   b) System Performance:
      - Real-time Processing: The system demonstrates the ability to apply this anomaly detection rule in real-time on streaming data.
      - Data Integrity: Preservation of original data allows for post-analysis and verification.

   c) Operational Insights:
      - The system effectively identifies periods of high combined voltage and current, which could indicate:
      ✓ Peak load periods
      ✓ Potential overload conditions
      ✓ Times of high power transfer between grid sections

   d) Data Utilization:
      - The comprehensive data collection allows for:
      ✓ Correlation of anomalies with other grid parameters
      ✓ Long-term trend analysis of grid behavior
      ✓ Potential for predictive maintenance based on recurring patterns

The proposed system successfully implements a straightforward but effective anomaly detection method for smart grid data. It consistently identifies periods of high combined voltage and current, which are indicative of significant grid events or conditions. The system demonstrates robust real-time processing capabilities and maintains data integrity, providing a solid foundation for grid monitoring and analysis.

5. CONCLUSION

The increasing vulnerability of smart grids to cyber-physical threats necessitates advanced detection systems that balance accuracy, speed, and deployability. This study presented an integrated machine learning (ML) framework for real-time anomaly detection in smart grid data streams, combining Apache Kafka for high-throughput data ingestion, Kubernetes for scalable orchestration, and rigorous benchmarking of five ML models. The Random Forest algorithm demonstrated exceptional performance, achieving near-perfect metrics (F1-score: 0.9982, precision: 0.9987, recall: 0.9978), while maintaining a compact model size (6.32 MB) suitable for edge deployment. The Kubernetes-managed Kafka pipeline enabled real-time processing of 1,000 messages per second with ≤200 ms latency, validating its capability to handle streaming data under operational conditions.
Key contributions of this work include:

- Comprehensive Model Benchmarking: A systematic comparison of five ML algorithms, revealing Random Forest's superiority in capturing decision boundaries within highly separable smart grid data.
- Scalable Architecture: A Kubernetes-driven deployment of Kafka, ensuring fault tolerance and modularity for real-time data ingestion, preprocessing, and anomaly detection.
- Practical Relevance: A deployable solution that preserves raw data for post-analysis while providing actionable insights through real-time dashboards, aiding grid operators in mitigating threats like voltage surges and load imbalances.

Limitations and Future Work:

- While synthetic datasets provided controlled testing, future validation with real-world attack scenarios is critical.
- The single-node Kubernetes cluster, though effective, requires stress-testing on multi-node cloud environments to assess horizontal scalability.
- Integration of adaptive response mechanisms (e.g., automated load redistribution) could further enhance system autonomy.

This framework bridges the gap between theoretical ML research and operational smart grid security, offering a blueprint for resilient infrastructure. By prioritizing both algorithmic accuracy and engineering pragmatism, it advances the transition from reactive to proactive grid management in the face of evolving threats.

Impact Statement: The proposed system's low-latency detection capabilities and modular design position it as a viable tool for utility providers seeking to modernize grid security without compromising computational efficiency.

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Event-Based PI Control Applied to Laboratory Plant

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Abstract: In this research, event-based PI controllers is implemented to control a liquid flow-rate in a laboratory plant. With the emerging technologies like Industry 4.0 and IoT, the Networked Control Systems (NCSs) are said to be wirelessly connected in the distributed process industries, thereby reduction in signal transmissions, CPU utilization and power consumption. The flow-rate valve actuator transfer function is identified as a first-order plus dead time (FOPDT) using the open-loop reaction curve of the plant and it is tuned with the SIMC-PI tuning method. A time-based PI controller is designed and simulated on the plant with event-based PI controller techniques. This is further improved as an advanced type of event-based PI strategy (PIDPLUS controller) **to** improve the performance. The**se** techniques are implemented and simulated in the MATLAB/SIMULINK workspace aided by OPC toolbox that provides the interface for laboratory plant data reading and control. The emerging technologies used in this research can be employed by the industries in PNG to enhance their productivity and performance.

Keywords: NCSs, event-based PI, SIMC-PI, sticking effect, oscillatory behaviour, PIDPLUS.

1. INTRODUCTION

The proportional-integral-derivative (PID) controller is the most widely used closed-loop control mechanism in industry, particularly in process and manufacturing industries. There are many variants of PIDs: ideal, parallel, series, one degree of freedom (1DoF), two degree of freedom (2DoF), etc. Most of such controllers are implemented as proportional-integral (PI) controllers, since the derivative action is frequently not used in industrial process control applications due to its noise amplification effect. Traditionally, the control systems used in implementing PI and PID controllers have been based on periodic sampling (time-based), for which data transmission between controller agents like sensors to the controllers and actuators are done periodically.

However, nowadays in response to global competition and the fast adoption of production to the ever-changing market request, radical advances in non-centralized and distributed industrial process technologies have introduced networked control systems (NCSs). In the likes of emerging technologies like Industry 4.0 (Y. Lu., 2017), Internet of Things (IoT) and 5G evolutions where the closed-loop is wirelessly connected; one should consider the trade-off in scarce resources like bandwidth, energy consumption and CPU utilization of embedded processors and industrial computers that perform control actions. Additionally, the wireless network may induce network congestion which could result in large communication delays and loss of information, which greatly affect the process controller performance. Hence, there is a significant increase in research in the last decades that proposed several event-based controller structures and PI tuning methods (Heemels, 2013; Poveda, 2017; Borgers, 2017). Figure 1 shows a typical wirelessly connected control agents of a distributed industry.

Event-based control, referred to as aperiodic or asynchronous where sampling is event-triggered rather than time-triggered (Arzen, 1999). The event-based control technique is a new control method that closes the feedback loop only if the error signal exceeds a predefined threshold. In this method, data transmission between the controller agents are asynchronously triggered, thus reducing the number of signal transmissions. Also, when not actively engaged in transmitting or processing signals, sensor nodes and controllers can be put in sleep mode to save energy. The use of event-based controllers (including event-based PID) have to renounce to a very sizeable part of the linear control system theory, to make an appeal to

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ad hoc solutions or less developed notions such as one provided by the theory of hybrid systems, efforts in trying out and comparing different alternatives are very much welcome.

The event-based PI (EPI) is implemented in the present research what constitutes an ongoing very active effort in academia and industry. The two EPI controllers are compared with a traditional timed-based PI (TPI). The comparisons are made initially in simulation and then they are applied to the control of flow-rate on a real laboratory plant. In order to produce a fair comparison both EPIs are compared with a correctly tuned TPI as per tuning rules (Dwyer, 2009). Here, the methodology (Grimholt, 2018) as applicable to the control of FOPDT processes is used. Many tuning rules, offers a single set of values for the parameters of the PI(D). The SIMC tuning rule offers a simple and intuitive single parameter tuning that help the designer to make the trade-off between the required degree of aggressiveness and robustness.

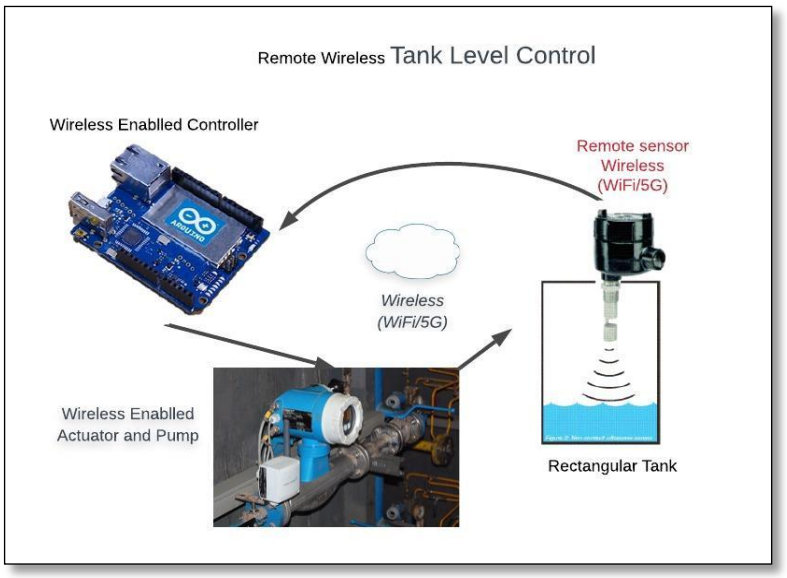

Figure 1: Wireless control of a tank level

The results produced in this research signify a promising solution for distributed industrial settings employing NCSs by attaining similar system performance as in TPI controllers by reducing signal transmissions with the proposed EPI controller algorithms. The benefits of reducing signal transmissions from controller agents are reduced network congestion that may induce network delays and loss of viable data transmissions, improved CPU performance of controllers and efficient use of energy for battery powered controller agents. The MATLAB/SIMULINK (Natick, 2019) environment is used in development. It is used for gathering sensor data from the real plant, to identify dynamics of the flow-rate valve, to create the model of reference TPI, and of the two EPIs, to perform simulations and finally to control the real plant flow-rate actuator with the coded controllers. The interface between MATLAB/SIMULINK and laboratory plant has been achieved using the OPC toolbox, an implementation of the known interoperability protocol (Zamarreño, 2014).

2. LABORATORY PLANT AND MATLAB/SIMULINK OPC TOOLBOX

2.1 Laboratory Plant

A heat exchanger is a mechanical device used particularly for heating and cooling applications where internal thermal energy is transferred between two or more fluids available at different temperatures. Heat exchangers are widely used in industries like process and manufacturing, power, petroleum, transportation, air-conditioning, refrigeration, and other industries. Figure 2 shows the heat exchanger laboratory plant used to implement the proposed event-based PI controller. The flow-rate valve actuator is considered the system of interest where a

FOPDT model is identified, tuned with SIMC method (Grimholt, 2018) and the proposed event-based PI control algorithm is tested and implemented.

2.2 MATLAB/SIMULINK OPC Toolbox

The MATLAB/SIMULINK Open Process Control (OPC) (Drahoš, 2018) toolbox, also known as OLE for process control, is a series of seven specifications defined by the OPC Foundation for supporting open connectivity in industrial automation. The Microsoft DCOM technology is used in OPC to provide a communication link between OPC servers and clients that enhance reliable communication of information in an industrial process plant. In this research, an OPC custom server was configured and interfaced through a USB-1408FS-Plus data acquisition card that communicates to the OPC clients. This setup allows for the reading of sensors values to the controller and for writing actuator values. The OPC interface allows the connection of the MATLAB/SIMULINK coded controller to the sensors and actuators for the closed loop feedback control. The OPC Simulink model used is shown in Figure 3 where an open-loop step test is performed for FOPDT model parameter identification for derivation of system transfer function.

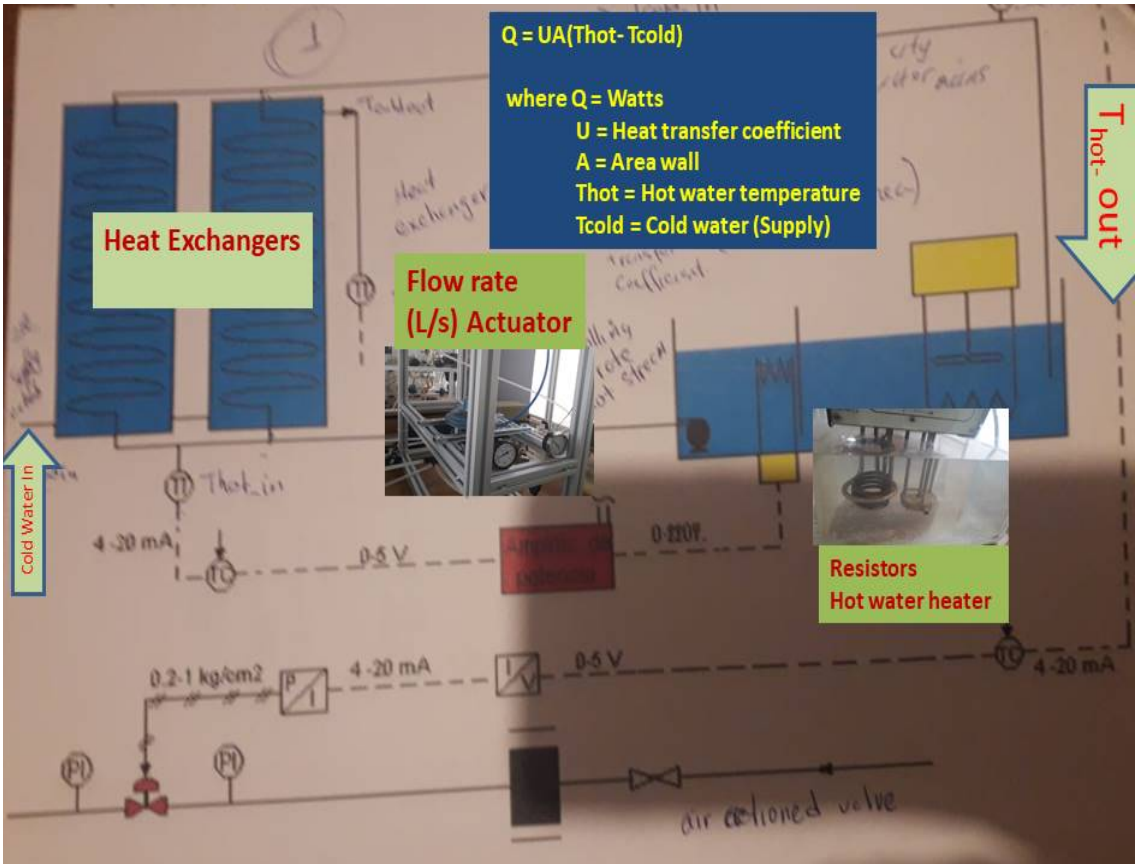

Figure 2: Schematic of the heat exchanger laboratory plant

In the Figure 3, OPC Read block (1) reads the value provided by the flow-rate sensor and made available in the input signal line (in_Volts03) of the OPC server. Depending on the changes in position of the step input block (2), the OPC Write block (3) writes the valve actuator signal via output/control signal line (out_%01) which corresponds to the opening of the control valve. The gain block (2.09) and the negative constant block (-1.82) are the slope and intercepts respectively for the linear calibration of the input sensor signal (y(t)) into its physical quantity (litres/seconds). The simulation output is shown in Figure 4 that shows the plots of step input (u) and system output (y) with respect to time (t) which is used for the identification of the model of the plant.

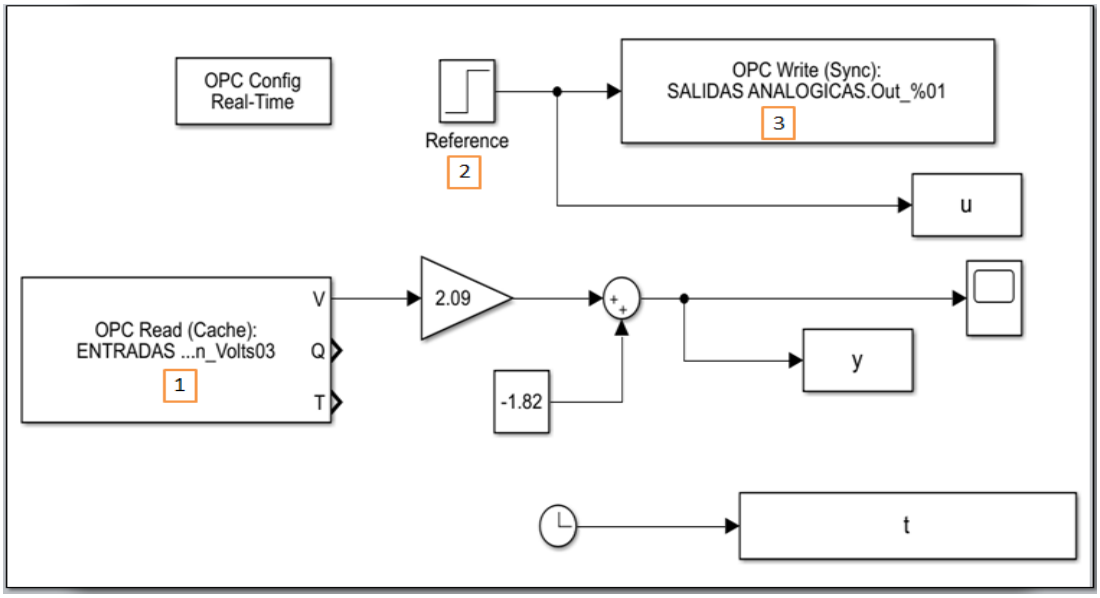

Figure 3: OPC MATLAB/SIMULINK model setup for obtaining reaction curve

3. IDENTIFICATION OF TRANSFER FUNCTION PARAMETERS AND TUNING WITH SIMC AND TPI

3.1 Identification of Actuator Transfer Function Parameters

Identification of transfer function parameters of flow-rate is a necessary requirement for implementation of PI/PID controller tuning. The transfer function of flow-rate actuator valve was derived from the data labelled in Figure 3, given a step input signal assuming the valve was initially closed or at rest. This identification process is known as step test, generally performed in terms of an open-loop control structure. Figure 4 shows the reaction curve of dynamic system response of the flow-rate actuator valve.

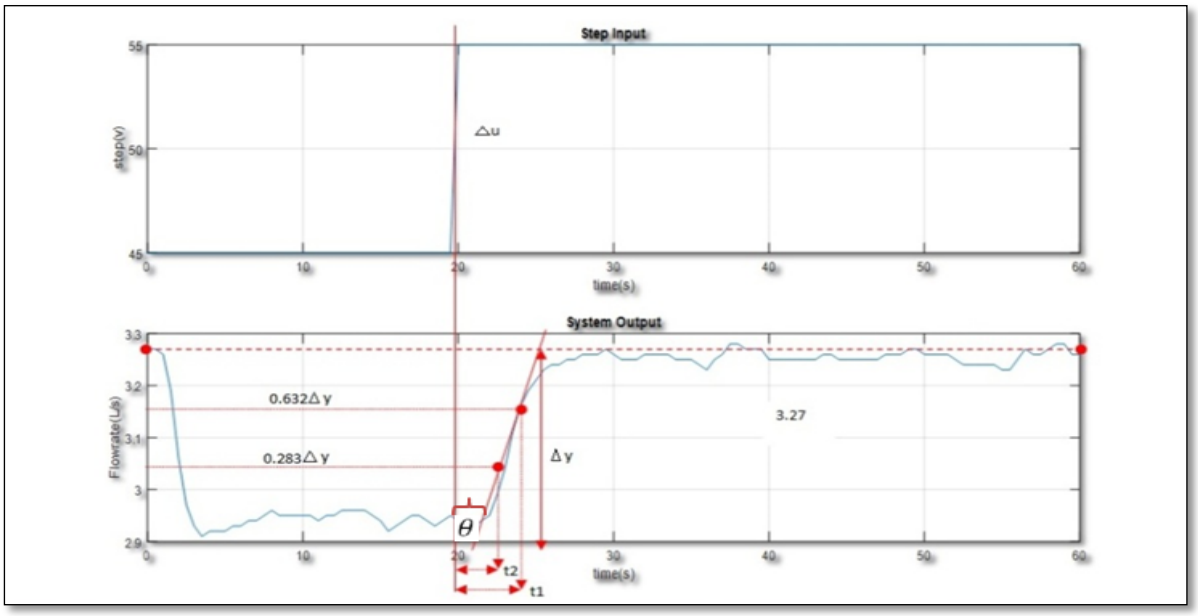

Figure 4: Open loop reaction curve of the flow-rate valve actuator.

A step test at simulation time of 60 seconds yields Figure 4 in which a linear FOPDT model was considered mainly for parameter identification. Generally, the FOPDT model is of the form

$$G(s) = \frac{K*e^{-\theta s}}{\tau s+1} \quad (1)$$

where K depicts process gain, θ process time delay in seconds, and τ process time constant. The calculations for system transfer function parameters using figure 4 give

The Process Gain

$$K = \frac{\Delta y}{\Delta u} = \frac{0.37}{1o} = 0.037 \quad (2)$$

Process Time Delay

$$\theta = t1 - \tau = 3.134\text{-}0.194 = 2.941$$

Process Time Constant

$$\tau = 1.5(t1 - t2) = 1.5\ (3.134 - 3.01) = 0.194$$

The equation (2) is the transfer function of the flow-rate actuator valve of the heat-exchanger plant, where the proposed event-based PI controller is tuned and implemented.

3.2 Tuning of Time-Based PI with SIMC Tuning Method

The PI controller is widely adopted in process industries, while the D-term (derivative) is, in many occasions, neglected to reduce the propagation of amplified random measurement noise via the controller. Given the flow-rate valve actuator transfer function in (2), the challenge now is to apply a proper tuning technique to control the flow-rate valve actuator and to remain in the linear region of the actuator saturation. The transfer function of an ideal PI controller is given in (3),

$$Gc(s) = Kp(1 + \frac{1}{Tis}) \quad (3)$$

where *Kp* is the proportional gain and *Ti* is the integral time constant. The PI controller in its digital equivalent is given in (4),

$$xc(t_{k+1}) = xc(t_k) + \beta(t_k)\,(r - y(t_k)),$$
$$u(t_k) = Kp(r - y(t_k)) + \frac{1}{Ti}xc(t_k) \quad (4)$$

where xc is integrator state, Kp is proportional gain, Ti is integration time, $\beta(t_k)$ is integrator update rate, r is reference signal usually constant, $y(t_k)$ is system output and t_k is time instant in at which a new control input is computed.

A better tuning is achieved by obtaining optimal PI settings, which by definition is the minimum integrated absolute error (IAE) to disturbances for a given robustness level with less response time (Grimholt, 2018). A very simple yet effective methodology for tuning PI(D) controller for different type of plants are the SIMC rule discussed in (Grimholt, 2018). An important plus for adopting SIMC is that it provides an easy way for helping the designer to choose a particular tuning in continuous spectrum. The spectrum encompasses a range of equally effective tunings but that result in different closed loop dynamic behaviors which go, from a very aggressive, rapid and oscillatory response at one extreme, to a smooth, slow, very robust dynamics at the other. Thus, SIMC rule is the systematic approach adopted for this research.

3.2.1 SIMC Tuning Method

The SIMC turning rule (Skogestad, 2004) works well for both pure time delay and integrating processes and for both set-point tracking and load disturbances rejections. The original SIMC rule is of the form:

$$kc = \frac{1}{k}\frac{\tau}{(\tau c+\theta)}, \ \tau i = min\ \{\tau, 4(\tau c + \theta)\} \quad (5)$$

where *kc* is gain of the PI controller to tune, τi is integral time of the PI controller to tune, the *k, τ, θ* are the identified FOPDT parameters of valve actuator in (2) respectively. The SIMC procedure is provided with a single tuning parameter τc which helps the designer to adjust desired close loop dynamics behavior of the PI settings which is much simpler with meaningful interpretation than adjusting *kc* and τi directly. The recommended choice for parameter tuning for optimal value of τc is determined by the trade-off between (i) quick system response and good disturbance rejection (small value of τc*)* and (ii) *s*tability, robustness and small input variation (favored by a large value of τc). Therefore, a good trade-off is recommended by choosing $\tau c = \theta$, which is for FOPDT models gives a reasonably fast response with moderate input usage and good robustness margins. Calculated in (2), letting the $\tau c = \theta = 2.941s$, *kc* and τi are now calculated as shown,

$$kc = \frac{1}{k}\frac{\tau}{(\tau c+\theta)} \approx 0.89 \qquad \tau i = min\ \{\tau, 4(\tau c + \theta)\} \approx 0.194.$$

Therefore, the $kc \approx 0.89$ and the $\tau i \approx 0.194$ are the tuned PI parameters of which a time-based FOPDT PI controller is designed, the base for fair comparison with proposed event-based counterparts. The tuned kc and τi parameters are used in event-based simulations for control of flow-rate valve actuator of heat exchanger laboratory plant.

3.2.2 Time-based PI Controller of FOPDT Model

Given the FOPDT transfer function of flow-rate valve actuator in (2) to be controlled by tuned PI controller, a time-based closed-loop PI controller with unity feedback is implemented. Figure 5 shows the implementation of time-based PI controller**.** The code in *Listing 1* is implemented in the user-defined MATLAB function block on the SIMULINK block diagram. The code includes an anti-windup mechanism. When the controller's output enters into valve saturation region (above 100% or below 0%) the summation represented by the integral term is stopped. With this simple measure in place, the very harmful windup phenomenon, that results in an unacceptable behavior is avoided.

For the time-base case, it is evident that the sampling is done periodically, since the number of samples/events of the system output shown in Figure 5(b) when implemented in the plant yields N = 10,000 samples. This is so because the simulation time of 200 seconds is evenly divided by the nominal sampling time. As a rule of thumb in control engineering for proper sampling of analog signals, the nominal sampling time is 10 times faster than the process time constant, that is $\tau/10$ ($hnom = 0.02\ s$). This increase in events due to periodic sampling is said to be greatly reduced as proposed with event-based techniques.

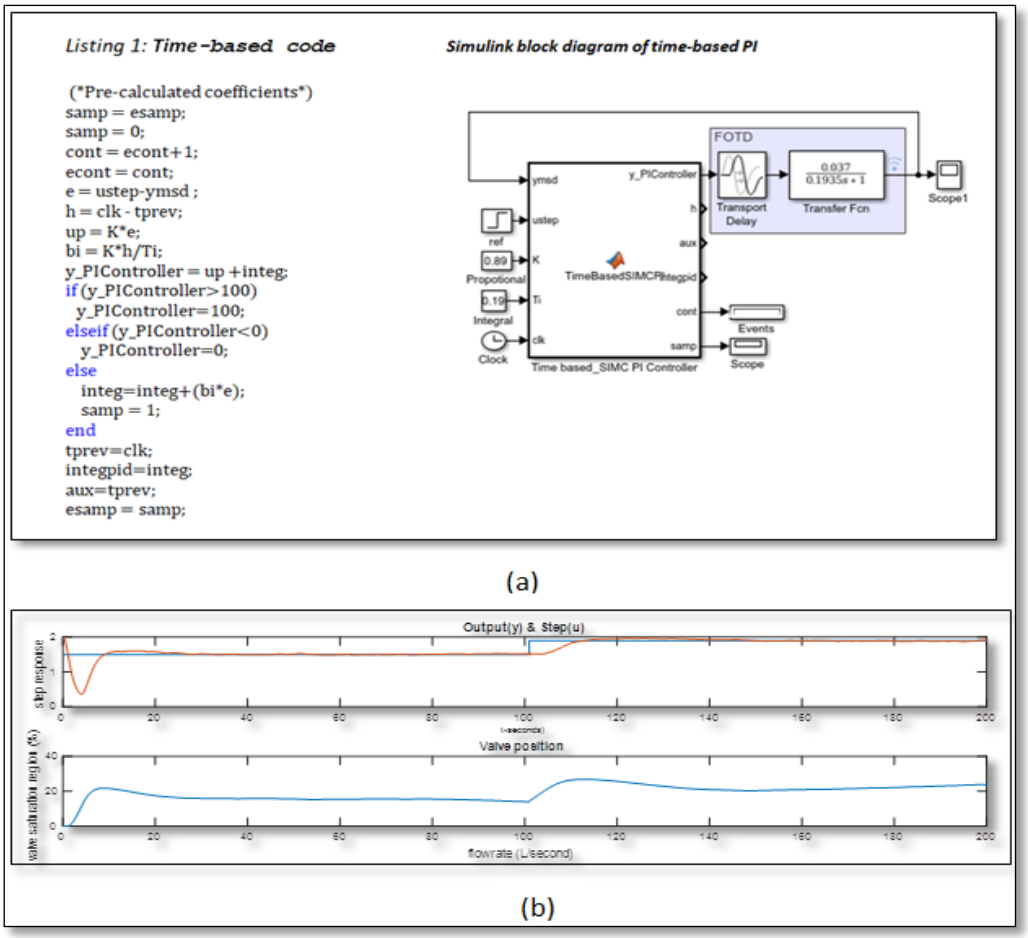

Figure 5: Time-based SIMC PI: (a) Listing 1: MATLAB code; Simulink model
(b) Output(y) and step (u); Valve position

4. SIMPLE EVENT-BASED PI CONTROL

As shown in time-based PI control Figure 5, even when the process output is around set-point, the signals are periodically sampled where no more transmissions would be required. This presents a challenge for distributed wireless NCSs where the control agents involved in the control loop are connected by Wi-Fi. The reduction in signal transmission is a relevant issue accounting for the scarce information bandwidth and network congestion that may lead to data loss and communication delays. Moreover, reduction in information flow will improve the CPU utilization (Arzen, 1999) for controllers, and saves energy for battery powered control agents.

To address these issues, event-based sampling and control technique has been used. This allows an efficient utilization of the network resources, while ensuring a desired behaviour of the closed-loop control system. This is achievable by transmitting information only when a certain threshold around the set-point is exceeded, where only then a control action is triggered. To achieve this, we introduce a new parameter namely a threshold around the set-point, $elim$. However, there are issues as pointed out by (Tiberi, 2012) that adoption of the event-based techniques may introduce *sticking* effect. With event-triggered controllers, it is in general impossible to reduce to zero the control error at steady state. This happens even in the presence of integral action in the controller. So, it is said that the error gets stuck on a finite, different from zero value, provided that this value is less than the pre-defined threshold. In many applications, like in Figure 1, the presence of a steady state error does not represent a major problem. In other cases, however, it is necessary to enforce a zero error. In this latter case, one would think that the problem could be solved by adding a time out (h_{max}) to the sampling rule, so

that the sensor is enforced to send a new measurement to the controller whenever the closed-loop system gets stuck, even when the threshold value is not surpassed. Thus, the new sampling rule is of the form:

$$\tau(t) = (|(e - eprev)| \geq elim)\text{OR}(hactual \geq hmax) \quad (6)$$

However, introducing the time-out barely solves the sticking effect but introduces another problem, which is the possible presence of sustained *oscillations* around the set-point. The increase in h_{max} increases oscillations around the set-point which then increases the number of events. Since the integrator update rate $\beta(t_k)$ is equal to the inter-event times h_k, if h_{max} is too large so it is $\beta(t_k)$. This is true because control input applied at time $t_{k+1} = t_k + h_{max}$ may be too aggressive and it potentially triggers an oscillatory behaviour of the output. Because of the sticking effect and the oscillatory behaviour of this simple event-based scheme, it is thus named a naive EPI controller. Figure 6 shows the MATLAB code and the Simulink model block diagram of the simple EPI controller. In order to realize the drawbacks mentioned, three test conditions (viz. Sticking Effect Simulation, Oscillations Around Set-Point Simulation, and Less Aggressive Tuning for Robust Response Simulation) are simulated to showcase the presence of the sticking effect, oscillatory behavior, and finally with a less aggressive tuning and selecting a reasonable time-out that at least cancels both the drawbacks.

Listing 2: ***Naive Event-based code***

```
(*Pre-calculated coefficients*)
e=ysp - ymsd;
h=clk-tprev;
bi=K/Ti;
hactual=hactualprev+h;
cont=econt;
samp=0;
if (abs(e-eprev)>elim || (hactual>=hmax))
  up=K*(ysp-ymsd);
  samp=1;
  eprev=e;
  y_controller=up+uiprev;
  ui=uiprev+bi*hactual*(ysp-ymsd);
  cont=cont+1;
  econt=cont;
  hactual=0;
  uiprev=ui;
  uprev=y_controller;
else
  y_controller=uprev;
end
esamp=samp;
tprev=clk;
hactualprev=hactual;
```

Simulink block diagram of naive event-based PI

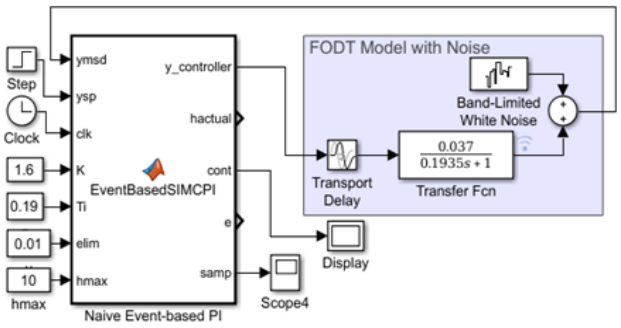

Figure 6: Simple event-based PI controller; Listing 2: MATLAB code, Simulink model block

4.1 Simulations of Simple EPI Applied on the Laboratory Plant

To validate the simulations, Simulink model in Figure 6 is implemented on the flow-rate actuator of the laboratory plant as in the time-based simulations for a fair comparison. We consider the sampling time $hactual = 0.02\ s$, as that of the nominal sampling time $hnom$ of the TPI, and following the same steps as in the TPI simulation, three separate simulations with varying $elim$ and $hmax$ are shown in Figure 7. The simulations are performed with a less aggressive tuning by setting Kp = 0.89, Ti = 0.19. Note that the noise signal and the FOPDT models blocks in the Figure 6 are replaced with the plant, via the OPC toolbox in MATLAB/SIMULINK interface.

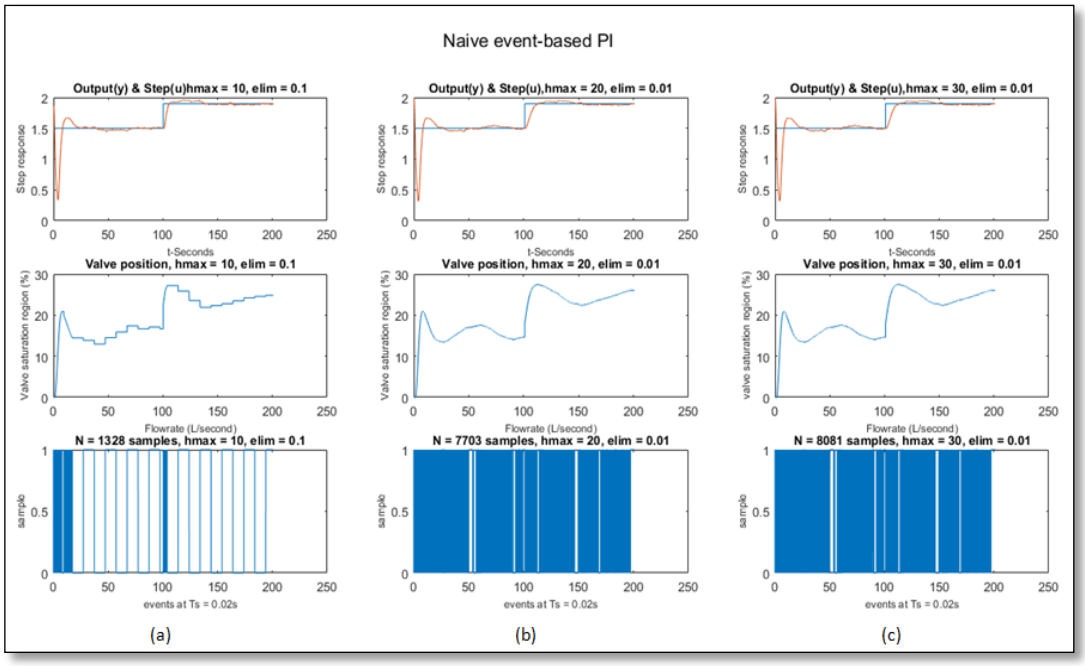

Figure 7: Simple event-based PI control: Laboratory plant simulations (a) elim = 0.1, hmax = 10 s yields N = 1328 events; (b) elim = 0.01, hmax = 20 s yields N = 7703 events; (c) elim = 0.01, hmax = 30 s, N = 8081 events.

From the simulations, it is seen that in the simple EPI the sticking effect introduces a non-zero steady state error, in spite of the presence of the integral action. The increase in the size of the $hmax$ introduces sustained oscillations around the set-point, resulting in a bad steady state behavior, and provoking the increase of the number transmissions, as can be seen in Figure 7 (b) and (c) having the same $elim = 0.01$. On the other hand, by choosing small values for $hmax$ to reduce the oscillation, we may lose the benefits of using the proposed EPI scheme since more transmissions are required. The simple event-based PI controller is further improved with the advanced event-based PIDPLUS at the cost of highest complexity.

5. ADVANCED EVENT-BASED PIDPLUS

The sticking effect and the oscillatory behaviour that presents in the earlier EPI controller are further improved with the PIDPLUS technique at the cost of a higher complexity. The complexity in the PIDPLUS version of the event-based controller presents then two degrees of freedom: one degree of freedom is represented by the selection of an appropriate design of the integrator update rate $\beta(t_k)$ implemented on the controller, while the other concerns the choice of a suitable event-based rule $\tau(t) \leq elim$ implemented on the sensor.

5.1 PI- based Triggering Rule

The PI-based triggering rule is introduced by (Tiberi, 2012) intuitively considering the dead-band triggering rule (Otanez, 2002) for an appropriate filtered version of the output signal. The filtered control input proposed is of the form:

$$\tilde{u}(t) = \acute{K}p\left(\left(r - y(t)\right) + \frac{1}{\check{T}i}\int_{tk}^{t}(r - y(s)ds + \tilde{}xc(tk)\right) \quad (7)$$

where $\acute{K}p$ and $\check{T}i$ are two shadow sampling parameters, and $\tilde{}xc$ is the shadow state of the integrator implemented on the sensor, thus they proposed the PI-based triggering rule denoted as

$$\tau(t) = \left|\tilde{u}(tk) - \acute{K}p\left(\left(r - y(t)\right) - \frac{1}{\check{T}i}\int_{tk}^{t}(r - y(s))ds - \tilde{}xc(tk)\right)\right| \leq elim. \quad (8)$$

Whenever the sticking effect occurs, the integral term in (8) grows unbounded, forcing the sensor to send a new event to the controller, thus avoiding the sticking effect. Moreover, the time-out in the simple EPI implementation is disregarded such that the controller is no longer updated if and only if $y_{k^*} = r$, that yields $\tilde{u}(t_{k+1}) = \tilde{u}(t_k)$ for all k greater than k^*. This is because when the system gets stuck, the sampling rule imposes a time-out that depends on the distance y_k from the set-point r. However, it should also be noticed that even if the triggering rule cancels the sticking effect and potentially sends a new control input $\tilde{u}(t_{k+1})$ straight to the actuator, the controller would be updated with $\tilde{u}(t_{k+1}) = \tilde{u}(t_k) \pm elim$. This control update rule leads to limit cycles that may generate unacceptable oscillation of the output. To avoid such oscillations, it is further proposed that whenever the sensor verifies that the PI-based triggering rule in (8) is violated, the sensor transmit to the controller the $y_p(t_k)$ instead of the value of $\tilde{u}(t_{k+1})$. Therefore, the controller updates the input signal according to the received measurement signal $y_p(t_k)$ and to the elapsed inter-event times.

5.2 Integrator Update Rate Adoption

The integrator update rate $\beta(t_k)$ is implemented on the controller and is of the from:

$$\beta(t_k) = Ti(\,1 - e^{\frac{-hactual}{Ti}}) \tag{9}$$

where Ti is the controllers integral time constant and the $hactual$ is the current inter-event period of the controller. For consistent results the formulation of the PIDPLUS as (11), with $\beta(t_k)$ as in (9). In (Tiberi, 2012), stability results of the proposed scheme are given, making use of advanced concepts of hybrid discrete-continuous theory that are well beyond the objectives of this project.

The MATLAB code in the *Listing 3* of Figure 8 shows the implementations of the advanced event-based PIDPLUS controller where the PI-based triggering rule as well as the integrator update rate are implemented. As in the simple EPI implementation, to visualize the achievements with the advanced event-based PIDPLUS controller, simulations at different test conditions are presented. Here the $hmax$ is set to infinity or neglected, since the tuning rule at the sensor side is determined by (8).

Listing 3: Advanced PIDPLUS event-based code

```
(*Pre-calculated Coefficients*)
e = ysp-ymsd;
h=clk-tprev;
bi=K/Ti;
hactual=hactualprev+h;
cont=econt;
samp=esamp;
bis=Ks*h/Tis;
xc=xcprev;
uiprevshow=uiprev;
error=abs(uprev-Ks*((ysp-ymsd))-xc-uiprev);
error1=Ks*(ysp-ymsd)+xc+uiprev;
error2=uprev;
if (abs(uprev-Ks*((ysp-ymsd))-xc-uiprev)>elim)
    up=K*(ysp - ymsd);
    if (samp==0)
        samp=1;
    else
        samp=0;
    end
    xcprev=0;
    xc=0;
    eprev=e;
    ui=0;
 y_controller = up+1*uiprev;
    if (y_controller>100)
        y_controller=100;
    elseif (y_controller<0)
        y_controller=0;
    else
         ui=uiprev+bi*Ti*(1-exp(-hactual/Ti))*(ysp - ymsd);
    end
    cont=cont+1;
    econt=cont;
    hactual=0;
    uiprev=ui;
    uprev=y_controller;
else
    ui=uiprev;
    y_controller=uprev;
end
xc=xcprev+bis*(ysp-ymsd);
xcprev=xc;
esamp=samp;
tprev=clk;
hactualprev=hactual;
```

Simulink block diagram of advanced PIDPLUS event-based PI

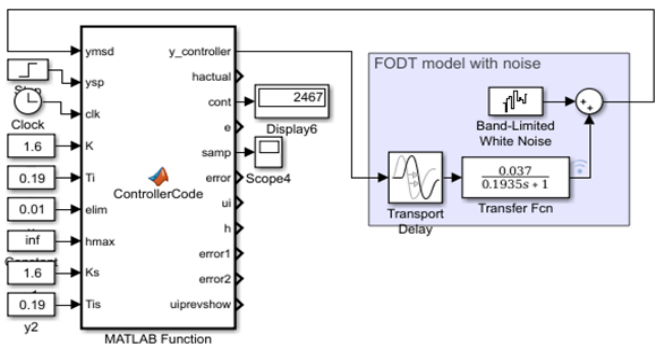

Figure 8: *Event-based PIDPLUS controller; Listing 3: MATLAB code, Simulink block diagram*

5.3 Simulations of Advanced Event-based PIDPLUD on the Laboratory Plant

As in the TPI and the simple EPI simulations, the advanced event-based PIDPLUS controller is implemented on the laboratory plant. Three different test conditions were simulated with varying $elim$ and the number of events transmissions were recorded as shown in Figure 9. It is noted that the computer simulations and with implementation on the laboratory plant, increase in $elim$ decreases the events transmissions and vice versa. Also, selecting different tuning of the parameters $\acute{K}p$ and $\check{T}i$ at the sensor and Kp and Ti at the controller has no restrictions.

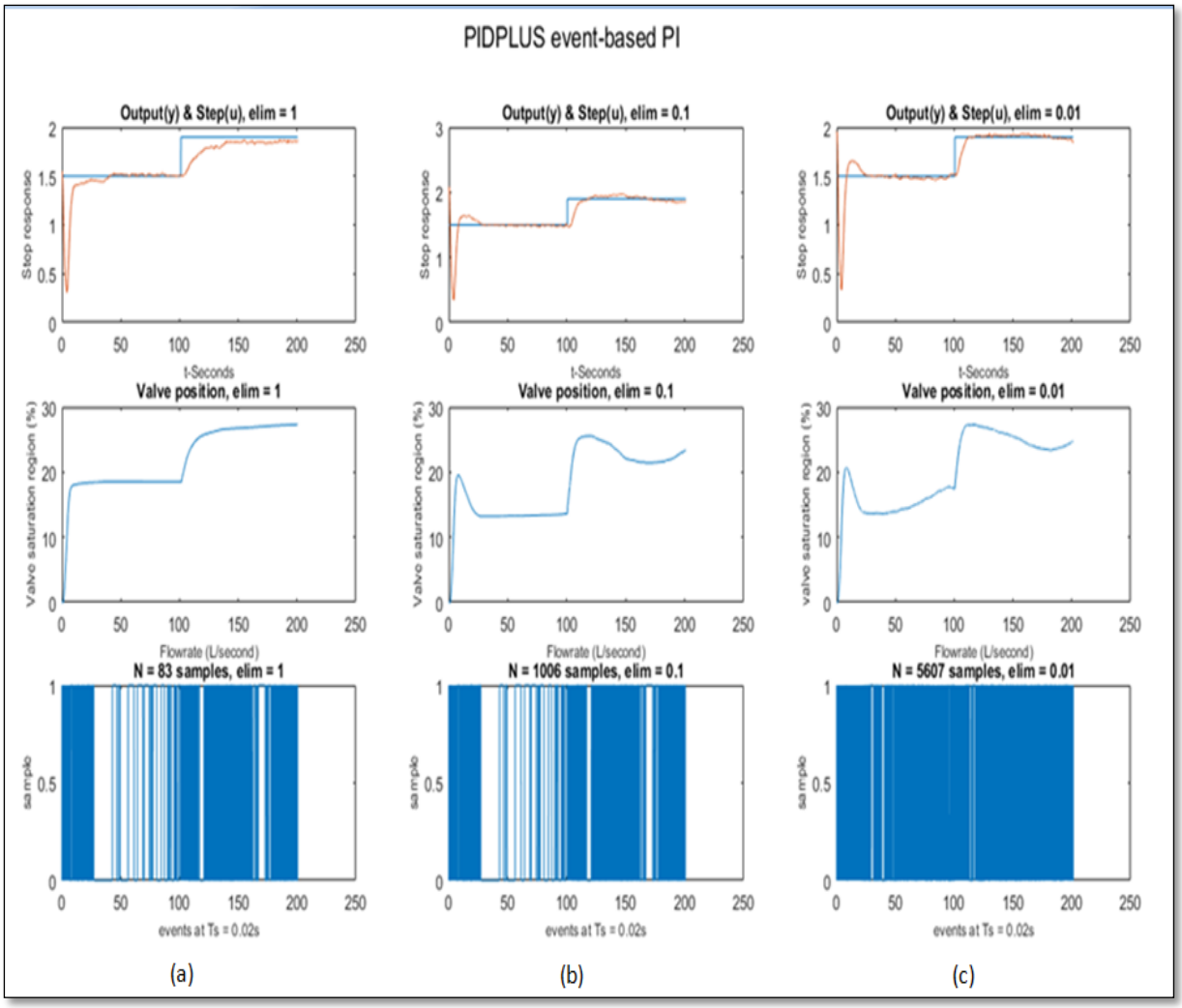

Figure 9: Advanced event-based PIDPLUS: Laboratory plant simulations: (a) elim = 1 yields N = 83 events; (b) elim = 0.1 yields N = 1006 events; (c) elim = 0.01 yields N = 5605 events.

A flowchart to distinguish the sensor and the controller algorithms for two event-based PI controllers is presented at Figure 10. Since the sensors and the controllers are located remotely and connected wirelessly, the algorithms are visualized separately for the simple EPI and the advanced PIDPLUS in the flowcharts shown in Figure 10. The flowchart implies the algorithms separately for simple EPI and advanced PIDPLUS controller at the sensor node and the controller respectively. Thus, the presented MATLAB codes shows that there is no difference in the results presented.

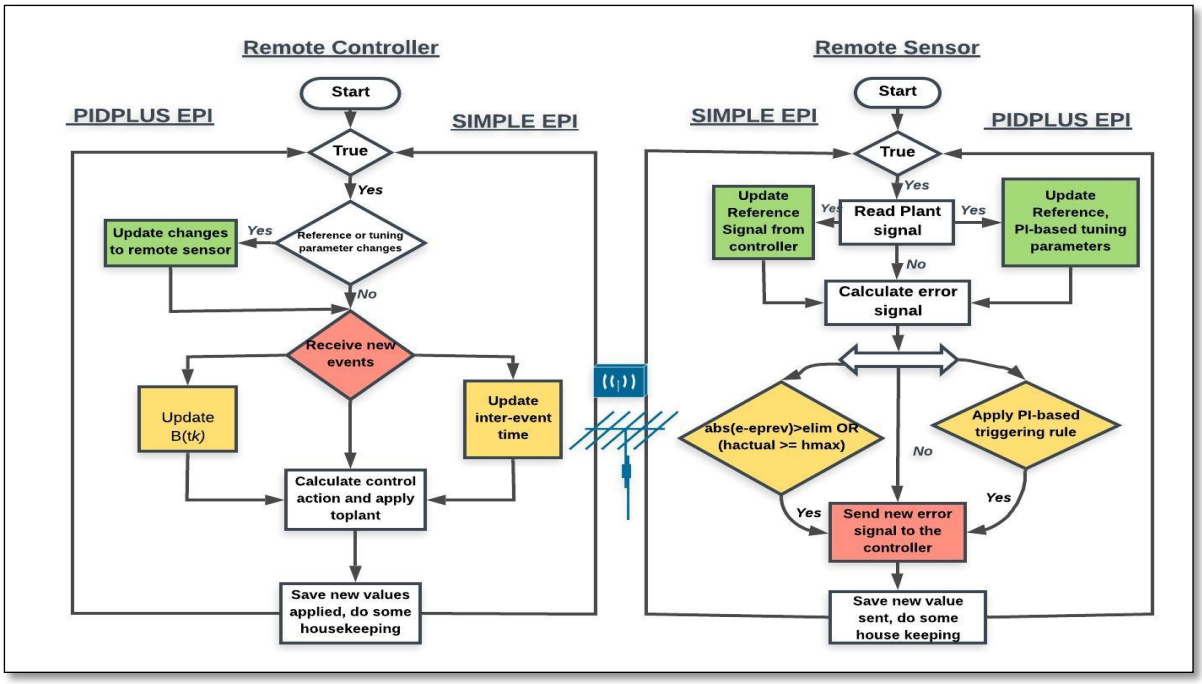

Figure 10: Algorithm flowcharts for Simple EPI and PIDPLUS at controller and sensor

6. RESULTS AND ANALYSIS

In this research, a systematic approach in implementing the proposed event-based PI controller of a linear FOPDT model is presented. Two distinct schemes have been designed and simulated; one being a simple EPI and other an advanced EPI with the PIDPLUS, which both seem promising for wireless NCSs over the traditional TPI methods. To better visualise the improvements in the traditional TPI over the proposed simple EPI and the advanced PIDPLUS, as far as reduction in events transmission is concerned, at several test conditions implemented on the plant, we obtain Table 1.

Table 1: Events transmissions at different test conditions of the laboratory plant

	Kp	*Ti*	*θ*	*hnom(s)*	*elim*	*hmax(s)*	*Events (samples)*
Time-based	*0.89*	*0.194*	*2.941*	*0.02*	–	∞	**10000**
Naive Event-based	*0.89*	*0.194*	*2.941*	*0.02*	1	∞	**91**
	0.89	*0.194*	*2.941*	*0.02*	0.1	10	**1328**
	0.89	*0.194*	*2.941*	*0.02*	0.1	20	**1678**
	0.89	*0.194*	*2.941*	*0.02*	0.1	30	**1943**
	0.89	*0.194*	*2.941*	*0.02*	0.01	10	**6885**
	0.89	*0.194*	*2.941*	*0.02*	0.01	20	**7703**
	0.89	*0.194*	*2.941*	*0.02*	0.01	30	**8081**
PIDPLUS Event-based	*0.89*	*0.194*	*2.941*	*0.02*	1	∞	**83**
	0.89	*0.194*	*2.941*	*0.02*	0.1	∞	**1006**
	0.89	*0.194*	*2.941*	*0.02*	0.01	∞	**5607**

The data presented in Table 1 is with the similar parameter settings and tested for a duration of 200 seconds duration time at sampling rate of 0.02 seconds. The number of events transmissions are reduced with the proposed EPI compared to that of TPI where N = 10,000 samples.

7. CONCLUSIONS

The adoption of wireless NCSs in the emerging technologies like Industry 4.0 and Internet of Things (IoT) reduces information transmission rate from controller agents with event-based techniques as compared to traditional time-based sampling techniques. An advanced event-based PIDPLUS model is designed to control the flow-rate of the heat exchanger laboratory plant using MATLAB/SIMULINK OPC toolbox. A time-based PI controller is designed and simulated for comparisons with the proposed event-based counterparts. These techniques are implemented, simulated and tested on flow-rate of the laboratory plant. Simulations and real data show reduction in signal transmission rate, less bandwidth usage, improved network congestions, improved CPU utilization and extended battery life reducing the need of regular battery replacements. This research uses emerging technologies viz Industry 4.0, Internet of Things (IoT) and 5G evolutions which can be employed by the industries in PNG to enhance their productivity and performance.

ACKNOWLEDGMENT

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Analysis of Cyber Security Challenges in Smart Grids

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Abstract: A Smart grid is generally an electrical grid combined with the best of digital technologies. The benefit of this shift, though very dependent, efficient, and sustainable, also has a lot of cybersecurity risks. Modern energy systems are based on the smart grid, which is vulnerable to hackers and hence threatens the safety of public and economic activities. In this study, we provide a thorough analysis of Smart Grid cybersecurity concerns. One of the major issues with a smart grid network has been security; up until now, cybersecurity has been the main factor to be taken into account. Again, it took a lot of investigation to uncover those security flaws. Cybersecurity issues are continuously changing, especially those related to do with privacy, connectivity, and security management. Modern cybersecurity technology and best practices are mostly borrowed from the traditional telecommunications sector due to its laxer availability and safety standards. The oil and gas industry can provide very valuable inputs on how to handle all operational integration security issues; however, the smart grid faces a very different reality, with an extremely high number of end-users and very high geographic dispersion. Global growth in electricity demand necessitates the need to preserve the reliability, robustness, and safety of energy infrastructure, hence shielding smart grids against cyberattacks. Whoever is responsible will be able to adequately protect this vital piece of modern civilization's infrastructure against smart grid cybersecurity and, moving forward, implement remedial strategies before the threats. Only with strong partnerships working and striving in the right direction will we be able to address all aspects of smart grids associated maintenance challenges, delivering on that promise. A brief discussion on major cybersecurity concerns to a smart grid and some strategies for risk reduction is covered in the forthcoming section of this research.

Keywords: Cyber Security, Cyber-Attacks, Confidentiality, Integrity, Availability, and Smart Grid.

1. INTRODUCTION

All drawbacks, including energy storage to high-priced assets, frequent blackout incidents to sustainable carbon emissions, and blackout incidents in the last few years, have made the traditional power grid used for the delivery and distribution of power no longer viable. Research conducted at Berkeley National Laboratory estimated that the US economy has lost $80 billion a year; other estimates even go up to $150 billion per year, according to (El Mrabet et al. 2020). However, it was observed that sometimes, improving the efficiency of a traditional power grid required going one necessary step further. It is in this regard that microgrids were formed to improve traditional electrical grids.

Network inconsistencies, attack mitigation strategies, detection of cyberattacks, and resynchronization with the main grid have the potential to disrupt the networks. All these were presented as problems and obstacles. Therefore, it was decided to portray the smart grid as a possible way of coping with these issues and stumbling blocks. Smart grids can implement two-way information flows, instead of only a one-way system from power plants to consumers like the traditional electricity grid. By enabling these communication systems and distributed control methods, they allow for functions such as demand response, where unused appliances are automatically turned on/promoted when there is abundant renewable energy available, or removing charging current, while at times using a limited carbon footprint.

However, there may still be problems regarding the smart grid. However, generation issues in electricity will brittle the smart grid's stability and may have high socioeconomic consequences. Therefore,

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Ricky Terry and Ashish Kumar Luhach | 2 (2) : 134 - 143

reliability, scalability, and interoperability are also changed in the electrical infrastructure. These issues are making the smart grid one of the growing interests to government, business, and academics (Framework., 2012). According to experts in security concerns related to smart homes and smart grids, smart grid technology is still in its infancy. These problems with smart grids, therefore, encourage us to look into smart grid cybersecurity problems more.

1.1 Background of the Study

The technological changes have marked the road that the present civilization has travelled, which is no exception in the case of the energy sector. The smart grid brought a sea change in the generation, distribution, and utilization of electricity. Digital communications, automation, and data analytics are put to work to create an intelligent and flexible energy distribution network. Due to the increased dependence on network devices and data-driven procedures, there are some cybersecurity risks, even though the Smart Grid is designed to enhance sustainability, dependability, and efficiency. This background study will identify, based on an examination of background information and implications, reasons, weaknesses, and possible threats, the focus on strong cyber defence in this important infrastructure - cybersecurity in the Smart Grid: Vulnerabilities, Threats, and Countermeasures.

Smart grids are sophisticated electrical systems that monitor, control, and optimize energy production, distribution, and consumption through the use of digital technology. Because of the difficult topography, dispersed population, and restricted access to dependable energy, particularly in remote regions, Papua New Guinea (PNG) is a prime candidate for smart grid technologies. Smart grid integration can help PNG's numerous decentralized energy sources, such as biomass, hydro, and solar. This method increases electricity reliability, lowers transmission losses, and improves energy efficiency. Additionally, smart grids provide automated responses, real-time monitoring, and quicker issue detection—all of which can drastically lower maintenance expenses and downtime.

1.2 Historical Background and Motivations

The idea of the smart grid emerged during the last decades of the 20th century, when technology became sophisticated enough to allow the monitoring and operation of energy networks more intelligently. In addition, the need to integrate renewable sources, demand response systems, and advanced metering infrastructure accelerated the transformation of conventional grids into intelligent network systems. The implementation of Smart Grids is for a number of reasons, which include handling increased energy consumption, reduction of greenhouse gas emissions, efficiency of energy, and making the energy infrastructure resilient. In contrast, the ecology of smart grids, upon growth, developed equal vulnerabilities to cyberattacks.

1.3 Features of Smart Grid

The fundamental benefit of smart grids is that they are projected to increase the resilience of the grid by making improvements to the environment. There are numerous problems with a power system’s resilience (Khoei et al., 2022). Suggested modifications may be made for its longevity and may ultimately have an impact on its predictability depending on environmental, technical, or even functional aspects. The capacity of a system to swiftly evade cyberattacks and continuously monitor its operation. The modern smart grid is more susceptible to instability and failure due to the increased unpredictability brought about by the quick development of technologies like dynamic pricing and microgrids. On the other hand, to recover from an agile and effective process, there will inevitably be a disruption of services and, more crucially, environmental circumstances.

1.4 The Intelligent Grid Conceptual Model

The smart grid vision consists of seven key logical components as defined by (Framework, 2012) in generation, transmission, distribution, markets and service providers operations. The actor’s type and also of the applications. Thus, actors is a systems and program, application tasks. But each of those domains have one or more players taking on these roles. The concept of smart grid is described in fig 1 below: Types of End-Users: Residential,

Business, Individual They are the key players in customer world It is also functionally closely intertwined with distribution, operation and service provider as well as market areas. The users operating within the market domain have to participate in the electricity markets as operators. Utility corporations and other businesses that can provide services to the customer are included in it.

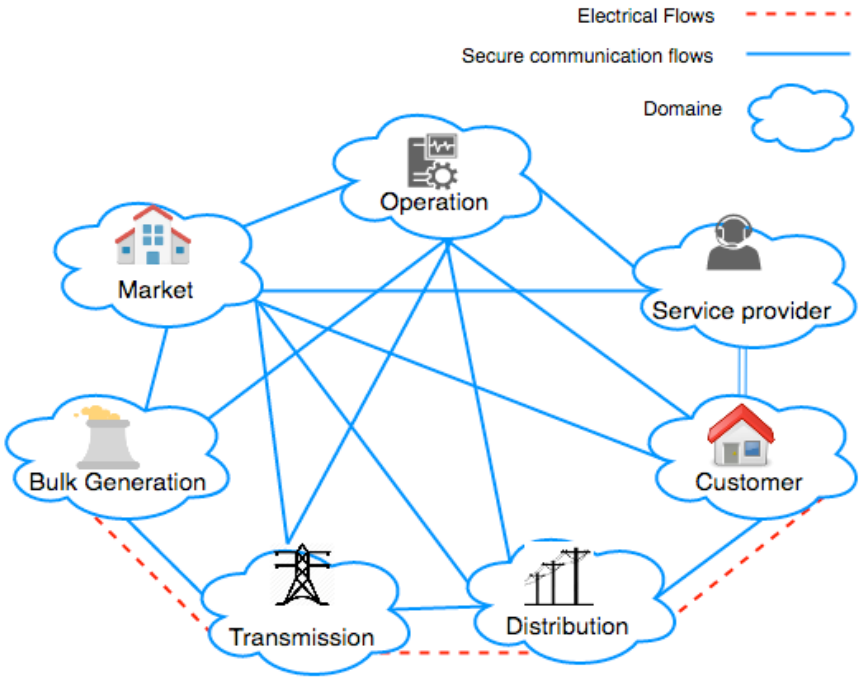

Figure 1: Conceptual Model of the Smart Grid

The ideas from this conceptual model above remain relevant to previous versions. The key insight the conceptual model offers is to the dichotomy between the increasingly sophisticated information exchange required to operate the grid and the relatively simple physical energy exchanges that comprise the grid. But even as the energy technologies of the system are diversifying and grid dynamics are becoming less predictable, electricity production and consumption remain dependent on a very small number of simple physical connections.

1.5 Technology for Smart Grid Communication

Ensuring safe, dependable, and up-to-date information about consumers and generation is crucial for effective electricity distribution in smart grids. Catastrophes, natural disasters, equipment failures, and accidents are the main sources of power distribution in smart grid systems. These issues can therefore be resolved by utilizing new information and communication technologies in conjunction with contemporary intelligent monitoring systems to securely transmit data between utilities and smart meters via wired and wireless communication. The following discusses a few wired and wireless communications technologies, as well as their benefits and drawbacks.

1.6 Smart Grid Communication Protocol

In order for various smart grid system components to exchange data and interact with one another, smart grid communication protocols are required. Utilities can effectively supervise, manage, and keep an eye on the grid remotely thanks to these protocols. Smart grids use various communication protocols, each of which serves a distinct function and functions at a different level of the communication hierarchy. The primary element utilized in SG to guarantee end-to-end data communications is the Transmission Control Protocol/Internet Protocol (TCP/IP). It isn't always a suitable choice for SG networks, though. Certain protocols have been created to satisfy the network needs of smart grids.

The smart grid infrastructure has two main components, SCADA and AMI. In order to implement capable, responsive and secure communication amongst these devices some ensures like the below mentioned

were developed in recent years: On Another Hand SCADA Communication Depending on Different Smart Grid Protocols Including Distributed Network Protocol version 3 (DNP3), Modicon communication Bus (Modbus), Process Field bus (Profibus) and International Standard Defining communication protocol IEC61850. To connect smart meters with home appliances, AMI adopts various smart grid communication protocols but almost all of these possess variations in their security standards.

Gungor, et al., (2013) claims that DNP3 is the best communication protocol for power grid devices. Although DNP3 was utilized in the conventional power grid, its dependability, effectiveness, and compatibility over the prior version have led to its current utilization as the smart grid's data management solution. It is a widely accepted protocol in the electric utility industry for communication between various types of equipment, such as RTUs (remote terminal units), control centers, and intelligent electronic devices. It is super duper for serious and one-read person, debitters clarifiability robustise nationalelement encemageesc.

1.7 The Challenges in Smart Grid

Several infrastructure-related communication-related difficulties arise with the adoption of smart grids. In order to provide real-time data sharing between the various smart grid components, such as sensors, smart meters, and control systems, strong and secure two-way communication technologies are a major obstacle. It is therefore imperative to guarantee the resilience and dependability of communication networks, since any outages or cyberattacks may jeopardize the grid's operation and seriously jeopardize the stability of the energy infrastructure itself. A few of the threats to the security of smart grids are shown in Figure 2 below.

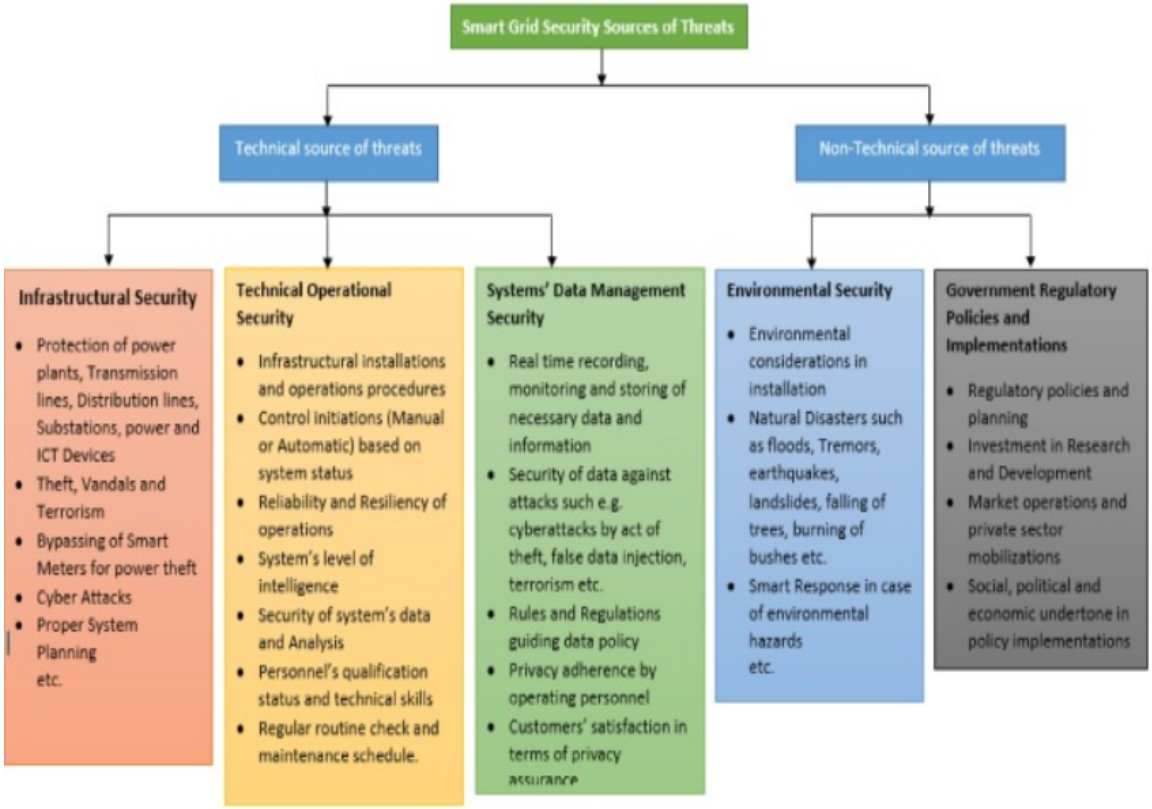

Figure 2: Security threats in the smart grid

1.8 Threats and Vulnerabilities in Smart Grids

Threats and vulnerabilities can also be divided into categories such as those pertaining to consumers, naturally occurring threats, threats to individuals and organizations, effects on consumers and availability, financial effects,

and attack probability. Attacks on SG can come in many forms, including malware, intrusion, routing, protocol-based, and denial-of-service (DoS) attacks, which can affect anything from home networks to generation and distribution.

In the worst instance, successful attacks may cause failure and blackouts, or grid instability. Staying out of trouble or identity and implementing countermeasures are prerequisites for a dependable security group. For communication encryption, integrity, and authentication within SG, protection should be employed. In addition, network attacks, DoS, Distributed Denial of Service (DDoS), Man-in-the-Middle (MITM), communications loss, and illegal access to networks and devices (eavesdropping) must all be addressed by security measures.

2. COMMUNICATION ARCHITECTURE

2.1 Communication Architecture in Smart Grid

In the smart grid, the infrastructure is built using a hierarchical architecture, which serves as a main building block. It joins a lot of systems and has only a few sub-networks. But each sub-network covers a comically small portion of the world. Smart grid network consists of WAN, NAN, and HAN are the main sub-networks as shown in Fig. 3. These three sub-networks by including the Field Area Network (FAN), Building Area Network (BAN and Local Area Network (LAN), a distributed version of the home area network (HAN) and personal area network (PAN) subnetworks, in order to achieve a better separation from BAN, as it is depicted in Fig.

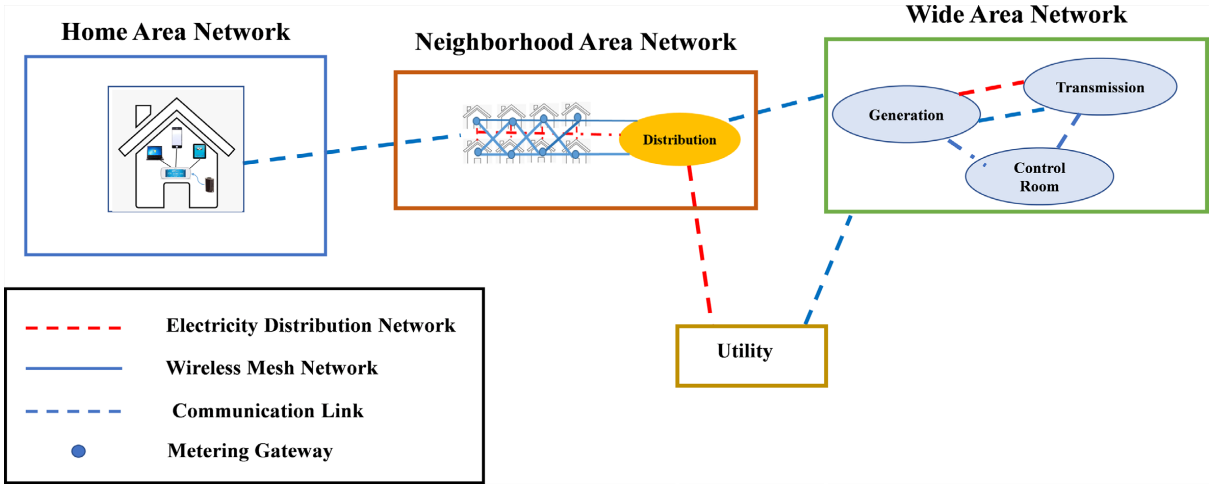

Figure 3: The smart grid architecture

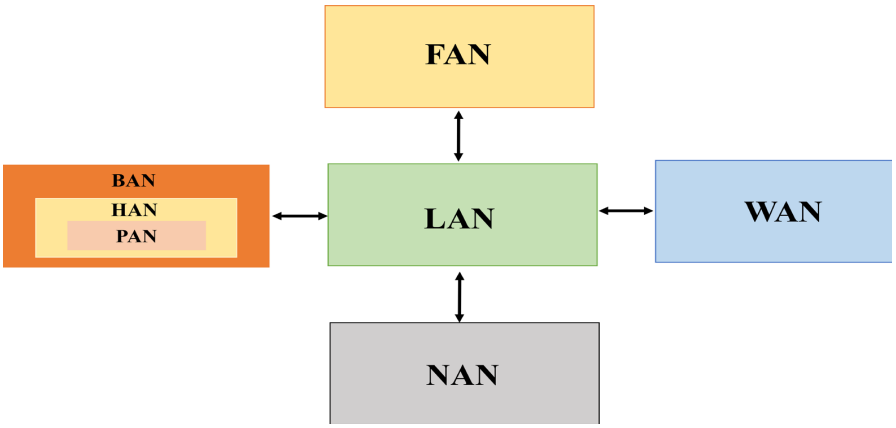

Figure 4: Types of communication networks in smart grids

WANs are the largest in terms of geographics coverage compared to local or neighbor networks. Even it may link other BAN/HAN/IAN or NAN/FAN networks. The introduced WAN as one of the most important networks in a smart grid architecture. Possible C r Core Network: It is a major network, which acts as an interconnecting backbone to join geographically distant small networks of power systems located at distinct places. It could also support, via broadband connections, long-distance data transmission and complex applications of monitoring/sensing. Bidirectional Device X: NAN automation, monitoring, and communication of smart grid systems. (S. G. I. Panel., 2010) Describe the NAN as a network designed to link WAN gateways and smart meters, distribution automation devices. It serves as a link between user properties and data concentrators, collectors, and access points at substations. It is possible to think of this subnetwork as having low capacity but strong resilience for safe data transmission. The NAN is a network that is supposed to link WAN gateways to smart meters and distribution automation devices. It serves as a link between user properties and data concentrators, collectors, and access points at substations. It is possible to think of this subnetwork as having low capacity but strong resilience for safe data transmission.

2.2 Smart Grid Security

Smart grids have supplanted archaic power systems in the last 20 years, which has made security quite a bit more difficult. To handle this, we have to develop a system and infrastructure with warranted secure architectural conditions. As a result, cybersecurity should be practised as part of an endless range of security standards without the need for it to arise on its own. (Blomqvist, K., et al 2008) states that the smart grid should secure itself with three requirements available confidentiality and integrity. Accountability also affects security in the smart grid.

It has been defined as providing timely and reliable access to and use of information. Hence, it is considered the most critical security requirement of smart grids because one cannot use the information without availability. For instance, unavailability can disrupt the control system from functioning because it blocks information from passing through the network, and hence making the network unavailable for the use of the operators of the system. According to DOS attacks are those that target the availability of a system through interfacing with data transfer and rendering resources unavailable. The attacks that result in DDoS and denial of service are for the purpose of removing the availability of a system. Thus, they can therefore delay, halt, or disrupt data transmission within the smart grid with the intention to paralyze it. Thus, it leads to a denial of data exchange or blackouts.

2.3 Countermeasures Significance

Such complex and evolving cybersecurity threats in the smart grid demand a proactive, diversified strategy that shall involve technological advances, regulatory standards, policy frameworks, and stakeholder collaboration. A set of variants of technologies-personal training, intrusion detection systems, real-time monitoring, encryption protocols, and incident response strategies-will help strengthen the defenses of the Smart Grid. Other than this, cybersecurity awareness and knowledge sharing are two other important ways of developing resilience in the energy ecosystem.

Cybersecurity has become increasingly critical with Smart Grid development from a concept to an omnipresent reality. This background study points out how vulnerabilities, new threats, and technological innovation are interlinked with each other in the smart grid technology context. By discerning all these features, namely the historical background, motives, vulnerabilities, and potential threats, an effective policy and countermeasure could be established by stakeholders in safeguarding the integrity, resilience, and capacity of the Smart Grid towards powering future civilizations.

2.4 Improving System Resilience and Mitigating Risks in Smart Grid

Improving system resilience and mitigating risks in smart grids is a multifaceted challenge that requires a coordinated effort from various stakeholders, including utilities, government agencies, cybersecurity experts, and the public. By enhancing cybersecurity measures, incorporating redundancy, implementing advanced monitoring systems, developing robust emergency response plans, promoting grid flexibility, encouraging policy support, and

fostering public participation, we can build a resilient and secure smart grid infrastructure. Such efforts are essential for ensuring a reliable energy supply in the face of evolving challenges and for advancing towards a sustainable energy future.

Smart grid electrical systems, which distribute energy in a dependable and sustainable manner, are essential to the smooth operation of our contemporary society. These systems are susceptible to equipment failures, cyberattacks, and natural disasters because of their growing complexity and interdependence. Thus, in order to guarantee a constant supply of electricity and minimal interference with the overall functioning of the grid, it is imperative that these systems be made more resilient. Algorithms for optimization are one way to do this; they can be used to find possible weaknesses, improve network efficiency, and speed up restoration in the event of an interruption. In the smart grid, reducing hazards and strengthening the system's resilience are essential to the system's sustainability and dependability. One component in these intricately linked systems has the potential to cause serious problems for the whole grid.

3. RISK ASSESSMENT AND IDENTIFICATION

3.1 Design of Resilient Smart Grid Infrastructure

a) Redundancy Infrastructure: Integrate redundancy into critical components and pathways within the smart grid. This includes duplicating power sources, communication channels, and critical control systems to ensure continuous operation in case of failure.

b) Distributed Energy Resources: Employ distributed energy resources such as solar panels, wind turbines, and energy storage systems throughout the grid. Such decentralized operation reduces the consequences of site-specific failure and increases the freedom within power management.

3.2 Analysis of Threats

a) Examining new cyberthreats, such as ransomware, malware, supply chain attacks, and insider threats, that are directed towards the Smart Grid.
b) Using threat intelligence feeds and past attack data to analyse the strategies, tactics, and procedures used by threat actors.

3.3 Cybersecurity Measures

a) Cyber Risk Assessment: The utilities shall periodically conduct cybersecurity assessments of the smart grid communication and control systems to identify their weak points. Emphasize malware, unauthorized access, and data breaches.
b) Encryption and Authentication: All the data to be transmitted within the grid should be encrypted, and access to the critical systems will be authenticated. Enforce MFA and strong encryption protocols to protect against cyberattacks.

3.4 Continuous Improvement and Evaluation

a) Performance Metrics: Establish KPIs for measuring the effectiveness of resilience measures. Monitoring this on a routine basis can help identify further scope for improvement.
b) Simulation and Testing: Regularly conduct simulations and stress tests to evaluate the grid's response to various risk scenarios. Use the insights gained to refine resilience strategies.

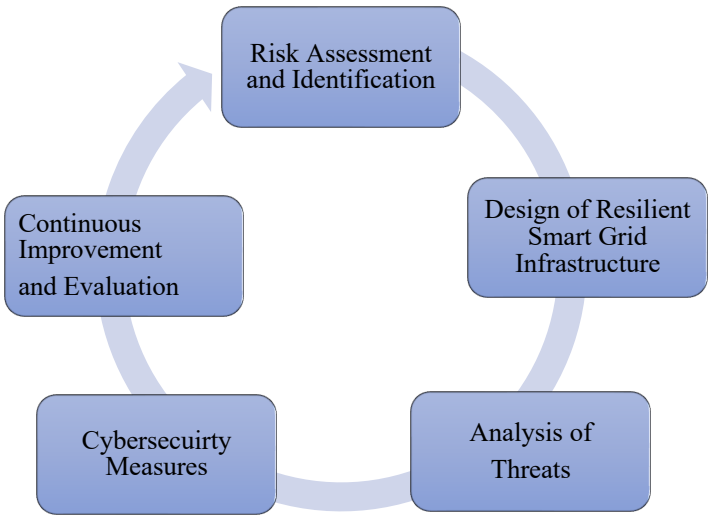

Figure 5: Flowchart of how to mitigate cybersecurity threats

The flowchart detailing the mitigation strategy for the smart grid in cybersecurity threats, as will be obtained from Figure 5, implies that an orderly process is implied in mitigating risks associated with cybersecurity threats to smart grid systems. Indeed, this orderly process encompasses several steps that ensure that the smart grid is resilient, secure, and adaptable to evolving cyber threats. Each of the above steps represents one part of an integrated process that includes the following: assessment and identification of risk, design of resilient smart grid infrastructure, threat analysis, cybersecurity measures, and continuous improvement and evaluation.

4. SMART GRID'S VULNERABILITIES

According to the analysis, there are several security holes in the smart grid system that might allow hackers to take advantage of them. Despite being necessary for the grid to function, legacy systems frequently lack contemporary security safeguards, leaving them vulnerable to attack. Even more so when combined with more recent, safe technologies, these outdated parts provide possible avenues of entry for hackers. Furthermore, because of inadequate device authentication and encryption standards, the growing integration of edge computing and Internet of Things (IoT) devices creates risks.

Furthermore, there are more opportunities for potential assaults because the Smart Grid depends on communication networks. The risk of illegal access and data interception is increased in these networks by inadequate authentication and encryption procedures. Moreover, uneven security measures result from the absence of standard cybersecurity procedures throughout the heterogeneous Smart Grid ecosystem, making some components more susceptible than others.

4.1 Emerging Threat Landscape

The research of the dynamic threat landscape brought to light the ways in which cyber adversaries are adapting their strategies to target the smart grid. Technological weaknesses and social engineering strategies are both used by nation-state actors orchestrating advanced persistent threats (APTs). Attacks using ransomware have grown to be a serious threat because they can affect vital grid components and have the ability to penetrate the infrastructure of the grid and potentially do extensive harm.

At the forefront of this problem are new dangers like ransomware, social engineering attacks, and advanced persistent threats (APTs). Because APTs are persistent and covert, they can enter networks without detection and gradually exfiltrate private information. Attacks using ransomware, which encrypts important company data and demands payment to unlock it, have become more frequent and severe, impacting businesses of all kinds. Human errors play a major role in successful breaches because social engineering techniques, such as phishing attempts, trick people into disclosing private information. Businesses must put in place efficient

defenses against these changing threats, which include a multi-layered cybersecurity approach. Shared threat knowledge, robust incident response plans, and real-time monitoring are all essential components of proactive defense methods. Developing comprehensive regulations, implementing state-of-the-art security technologies, and promoting a security-conscious culture among employees are further crucial components.

4.2 Integration of Threat Information

Threat intelligence is very important in bringing efficiency to active surveillance. Threat intelligence streams, when integrated, shall permit organizations to obtain current information about newly occurring threats, vulnerabilities, and modes of attack. The intelligence gained can be applied to enhance the monitoring process by enriching the context that aids security teams to prioritize responses and focus on the most relevant risks. Threat intelligence can be gathered from so many sources, including open databases, trade publications, and information-sharing groups. This kind of intelligence will enable an organization to understand the ongoing malicious cyber threats likely to affect its systems and applications. This proactive stance on intelligence enables the organization to exploit this for enabling it to adapt its monitoring tactics in search of peculiar dangers that face them.

5. NETWORKS CYBERSECURITY DISCUSSIONS

5.1 Data Encryption

Encryption Protocols: There are various efficient and strong cryptographic techniques that can be used in encrypting the data during transmission and at rest. Each substation, control centre, and smart meter will be capable of communicating with others.

The PKI allows secure key management for digital signatures and encryption that supports the identification of users and devices in the smart grid.

5.2 Incident Identification and Response

Continuous Monitoring: Automated technologies that inspect network traffic and system behaviour continuously monitor systems for suspicious activity or breaches.

Some strategies developed and implemented by organizations to counter cybersecurity incidents include containment strategies, eradication, recovery, and communication plans.

6. CONCLUSION

Smart grids are more capable and efficient than traditional power grids due to their higher level of environmental friendliness, wider utilization of renewable sources, and better security compared to conventional power systems. The report also mentioned certain advantages and disadvantages that can be associated with the smart grid. In a nutshell, it is beneficial to use the smart grid on account of enhanced security and multiple options that can be exercised regarding the Cybersecurity issue. Various studies that research has proposed have identified different types of security benefits and associated risks with smart grids. The denial-of-service attack has been identified as a potentially dangerous vulnerability for smart grids in almost all these studies. Since smart grids are essentially networks built on top of networks, a network attack would render a smart grid useless. Even though the Smart Grid will safeguard the availability of the service through several layers of protection, regarding security concerns, in that case, using a VPN is the best option for more secure communication.

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Sophisticated Machine Learning Methods for Reliable Network Traffic Data Categorization Models

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Abstract: Network traffic classification is critical for efficient network management, resource optimization, and security enhancement. The complexity of modern traffic patterns, driven by increasing user demands and diverse applications, poses challenges for traditional methods. This study explores advanced machine learning techniques to address these challenges, focusing on precise classification to improve network performance and detect anomalies effectively. The main key with machine learning such as Support Vector Machines (SVM), K-Nearest Neighbours (KNN), and Logistic Regression were evaluated for their categorization of the capabilities. SVM achieved an accuracy of 99.30%, while KNN and Logistic Regression excelled with accuracies of 99.92%. These results highlight the robustness and adaptability of these models to dynamic and complex network traffic scenarios. Accurate traffic classification facilitates informed decision-making in bandwidth allocation, congestion control, and service prioritization. Furthermore, these scalable models can adapt to evolving network environments and support data-intensive applications. This research demonstrates the transformative potential of machine learning in advancing network operations, offering a foundation for future innovations in intelligent, efficient, and secure network management.

Keywords: Network Traffic Classification, SVM, K-NN, Network Security, Resource Optimization, Traffic Pattern Analysis.

1. INTRODUCTION

Efficient network traffic classification is critical to modern network management, ensuring operational efficiency, optimal resource utilization, and enhanced security. The rapid growth of user demands and the increasing diversity of applications and services have introduced unprecedented complexity to traffic patterns. Traditional network management approaches often struggle to address these dynamic and intricate patterns, necessitating the development of more advanced methods for classification and forecasting.

This research focuses on leveraging state-of-the-art machine learning techniques to address the challenges of network traffic classification. Machine learning has proven highly effective in identifying patterns, adapting to diverse scenarios, and offering robust classification performance. In this study, three key algorithms such as Support Vector Machines (SVM), K-Nearest Neighbors (KNN), and Logistic Regression are evaluated for their ability to accurately classify network traffic. These models were chosen for their established strengths in pattern recognition and adaptability to evolving network conditions.

The study demonstrates that SVM achieves an accuracy of 99.30%, while both KNN and Logistic Regression reach an impressive 99.92% (Goyal, et al.). These results underscore the effectiveness of these machine learning models in managing the dynamic and unpredictable nature of network traffic. By accurately classifying traffic, these models enable network administrators to make informed decisions about bandwidth allocation, congestion management, and service prioritization, ultimately improving network performance and security (Goyal, et al.).

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In addition to classification, accurate network traffic forecasting is essential for proactive management and resource optimization. Advanced models, such as Enhanced Autoregressive Integrated Moving Average (ARIMA), play a pivotal role in predicting future traffic patterns. By incorporating historical data, time series analysis, and external influencing factors, Enhanced ARIMA models can capture seasonal trends and dynamic shifts in traffic, achieving high levels of forecasting accuracy.

This research highlights the transformative potential of combining machine learning techniques with advanced statistical models to revolutionize network management. These approaches provide scalable and adaptable solutions to meet the demands of modern, data-intensive environments. By addressing challenges such as non-linear traffic dynamics, resource constraints, and security risks, this study lays the foundation for intelligent, efficient, and secure network operations in an increasingly interconnected world.

This paper is organized as follows as Section 2 reviews related work in network traffic classification, emphasizing the evolution of machine learning techniques and their application in modern network environments (Goyal, et al.). Section 3 explores the challenges of traffic classification, including the complexities of dynamic traffic patterns, resource constraints, and security vulnerabilities in real-world scenarios. Section 4 outlines the methodology, covering data collection, preprocessing, feature selection, and the design of classification models using advanced machine learning techniques. Section 5 presents experimental results, analyzing the performance of the proposed models and comparing their accuracy and adaptability to existing approaches. Finally, Section 6 concludes the study by summarizing the findings and proposing future research directions for enhancing network traffic classification in increasingly complex digital ecosystems (Ouaissa, et al., 2025).

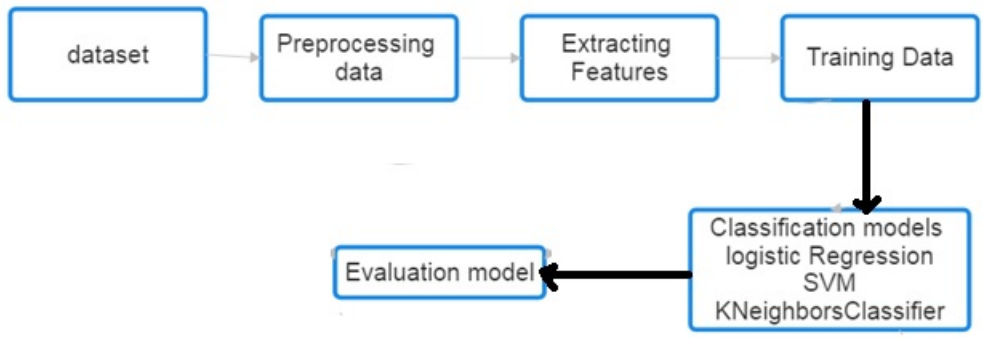

Figure – 1 Research Flow of Network Traffic Model

Figure – 1 is shown outlines a simplified workflow for a network traffic classification system using machine learning techniques. The process begins with the collection of raw data, typically in the form of network traffic logs containing attributes such as packet size, protocols, and flow durations. The data undergoes preprocessing to remove inconsistencies, handle missing values, and normalize the information, ensuring it is ready for feature extraction (Rana, Hossain, & Li, 2025). Relevant features are then extracted to capture critical characteristics of the traffic, such as protocol type, packet length, and flow statistics. These extracted features are split into training and testing datasets for model building.

The classification step involves training three machine learning models: Logistic Regression, Support Vector Machine (SVM), and K-Neighbors Classifier. Logistic Regression is effective for binary classification tasks, distinguishing between categories like normal and suspicious traffic. SVM is a robust classifier capable of handling complex decision boundaries in high-dimensional feature spaces. KNeighbors Classifier, a similarity-based algorithm, assigns labels based on the majority class among the closest data points. These models are trained using the training dataset to ensure they can accurately classify network traffic (Detection).

Finally, the trained models are evaluated using metrics such as accuracy, precision, recall, and F1 score to assess their performance and reliability in real-world scenarios. The updated diagram emphasizes classification-focused workflows by removing forecasting models and linking the classification outputs directly to evaluation. This end-to-end workflow provides a systematic and efficient approach to classify network traffic into predefined categories, enabling network administrators to make informed decisions about resource allocation, anomaly detection, and security management (Goyal, et al.).

2. LITERATURE SURVEY

Network traffic classification is a critical aspect of modern network management, facilitating efficient resource allocation, Quality of Service (QoS), and enhanced security. Over time, various classification algorithms have been developed to address the increasing complexity of traffic patterns. These algorithms range from traditional probabilistic models to advanced machine learning techniques, each contributing significantly to improving the accuracy and adaptability of traffic classification systems. Naive Bayes Classifier, for example, is a probabilistic model that assumes feature independence. Its computational efficiency and simplicity make it suitable for real-time traffic analysis, particularly in packet-level and flow-level classification scenarios.

Support Vector Machines (SVM) have been widely adopted for both linear and non-linear classification tasks. Known for their effectiveness in separating normal and anomalous traffic, SVMs are particularly valuable in intrusion detection systems due to their ability to handle high-dimensional feature spaces. Decision Trees and their ensemble extension, Random Forests, offer intuitive classification mechanisms. While Decision Trees provide transparency in rule interpretation, Random Forests enhance robustness and excel in managing complex, noisy datasets, commonly observed in network traffic.

Extreme Learning Machine Algorithms generally have a single layer hidden nodes whereby weights are assigned randomly in connecting. In order to reduce the computational complexity, Improved Error Reduced Extreme Learning Machine methodology was proposed as enhancement and also handle huge volumes of data. The results shown prove good improvement over traditional ELMs (Rajendran & Saravanan, Improved Error Reduced Extreme Learning Machine (IERELM) Classifier for Big Data Analytics, 2017, February; Vol 95; No 4;).

K-Nearest Neighbors (KNN) further contributes to network traffic classification by leveraging similarity measures in feature vectors. Its simplicity and dynamic adaptability make it reliable for diverse traffic scenarios. Neural Networks, particularly deep learning architectures like Convolutional Neural Networks (CNNs), have gained traction in recent years. CNNs excel in extracting spatial and temporal features, making them ideal for analyzing packet headers and traffic sequences. Logistic Regression, a binary classification algorithm, stands out for its straightforward implementation and efficiency in classifying traffic into normal versus suspicious categories. Bayesian Networks, with their probabilistic reasoning capabilities, model relationships between network features, offering strong anomaly detection capabilities.

Ensemble learning methods, including AdaBoost and Gradient Boosting, have been employed to enhance classification performance. These methods combine predictions from multiple classifiers to improve overall accuracy and robustness, making them ideal for network intrusion detection systems (Mohan, Sekhar, & Gupta, 2024). Recent advancements in machine learning have focused on integrating multiple algorithms, such as SVM, KNN, and Logistic Regression, to achieve classification accuracies exceeding 99% in real-world scenarios (Mohan, Sekhar, & Gupta, 2024). Furthermore, the incorporation of advanced forecasting models, such as Enhanced ARIMA, has demonstrated success in predicting traffic trends, addressing challenges posed by evolving and dynamic traffic patterns (Latifa, Ameni, Asma, & ribi, 2024).

A model developed on network intrusion detection using high performance deep neural networks proposed exhaustively evaluated the enhanced NSL-KDD dataset, giving a robust solution of ever evolving cyber threats (Rajendran & Saravanan, Big Data Analysis on Network Intrusion Detection using High Performance Deep Neural Networks, 2025, January;)

These research efforts underscore the transformative potential of machine learning and ensemble techniques in network traffic classification (Mohan, Sekhar, & Gupta, 2024). By combining computational efficiency, robustness, and adaptability, these methods address the challenges of increasingly complex and data-intensive network environments, ensuring secure and efficient operations while paving the way for future innovations in network management.

3. METHODOLOGY

The dataset for this research is collected using Wireshark, a widely-used tool for network protocol analysis. Network traffic data is gathered over six months during three specific time periods: morning, lunch hours, and afternoon (5 PM). The resulting dataset comprised approximately 50,000 entries and included attributes such as traffic volume, packet rates, and protocol types. The raw data is stored in formats like CSV and ZIP for ease of preprocessing and analysis. This comprehensive dataset served as the foundation for training and testing the classification and forecasting models.

Data preprocessing is critical to ensure the quality and usability of the collected dataset. Key steps included data cleaning, which involved removing duplicates, handling missing values, and correcting inconsistencies. Data transformation is carried out to aggregate data into meaningful time intervals (e.g., hourly or daily), normalize values, and handle outliers. Finally, feature extraction is performed to identify and extract relevant attributes such as traffic volume, packet rates, and protocol types. These steps optimized the dataset for the training of machine learning models.

The research employed advanced machine learning algorithms for traffic classification, including Support Vector Machines (SVMs), Logistic Regression, and K-Nearest Neighbors (KNN). SVMs were enhanced with a feature-weighted-degree (FWD-SVM) kernel to reduce the influence of weakly correlated and redundant features. Logistic Regression is applied to binary classification tasks, distinguishing between normal and malicious traffic, while KNN classified data points based on the majority class among their nearest neighbors in the feature space and the models were evaluated using metrics like accuracy, precision, recall, and F1 score for classification, Experiments were conducted under various network scenarios, including dynamic traffic patterns, peak usage times, and anomalous events resource allocation and detect security threats. The comprehensive methodology ensured robust and. These experiments assessed the adaptability of the models and their ability to optimize accurate models capable of addressing modern network management challenges. The Support Vector Machines (SVMs) with the enhanced feature-weighted-degree kernel can be expressed as:

$$\min \frac{1}{2}\|w\|^2 \quad \text{subject to} \quad y_i\,(w \cdot x_i + b) \geq 1,\ \forall i \tag{1}$$

where the kernel function K (xi, xj) is defined as:

$$K(x_i, x_j) = f_t \cdot (x_i \cdot x_j) \tag{2}$$

with ft representing feature importance calculated via information gain. This enhanced kernel ensures that features with higher classification importance are given more weight, improving overall model accuracy and robustness in handling network traffic data and Logistic Regression was employed for binary classification tasks, such as distinguishing between normal and malicious traffic. The model predicts the probability P (y = 1 | x) using this algorithm is particularly effective for tasks with clear binary outcomes and provides interpretable results, making it a reliable choice for identifying malicious traffic in network data. Its simplicity and efficiency make it well-suited for real-time classification which is define as

$$P(y = 1 \mid x) = \frac{1}{1 + e^{-(w \cdot x + b)}}. \tag{3}$$

and KNN classified traffic data based on similarity in feature space. For a given data point *x*, the Euclidean distance to its neighbors is calculated where xj and xi, j are the j-th features of x and xi, respectively. The data point is assigned the label of the majority class among its k nearest neighbors.

$$d(x, x_i) = \sqrt{\sum_{j=1}^{m} (x_j - x_{i,j})^2} \tag{4}$$

KNN is effective for locally smooth decision boundaries, though its performance depends on careful hyperparameter tuning and feature scaling for computer network classifications.

4. MODEL EVALUATION

The models are evaluated using the following metrics for accuracy where TP, TN, FP, and FN represent true positives, true negatives, false positives, and false negatives as follows as

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}}, \tag{5}$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}. \tag{6}$$

$$\text{F1 Score} = 2 \cdot \frac{\text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}}. \tag{7}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}. \tag{8}$$

5. EXPERIMENTAL RESULTS

Protocols play a vital role in network traffic classification within local area networks (LANs), significantly influencing traffic nature and optimization (Vajjhala & Strang, 2025). UDP is heavily used for quick, connectionless communication, often in time-sensitive applications like video streaming and DNS lookups, while TCP ensures reliable, connection-oriented data transmission for resource-intensive applications such as HTTP and email. Packet length analysis, with an average of ~1400 bits, provides insights into client-server and server-client communication, enabling the distinction between real-time and bulk data transfers. Application-specific protocols like HTTP/HTTPS, DNS, SMTP, and streaming protocols further refine traffic categorization. Accurate protocol analysis supports resource allocation, congestion control, anomaly detection, and bandwidth prioritization, forming a robust foundation for leveraging machine learning models in dynamic and complex network environments.

Figure – 2 the bar chart shown that distribution of network traffic across various protocols in a local area network (LAN). ARP is the most frequent protocol, exceeding 2000 occurrences, highlighting its role in resolving IP to MAC addresses, followed by DNS, which indicates frequent domain name resolution requests.

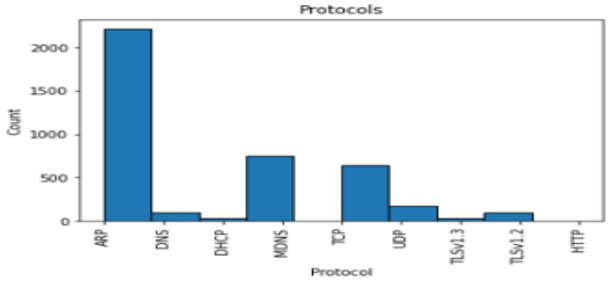

Figure – 2 List of Protocols

Moderate usage of DHCP and MDNS suggests dynamic IP assignment and local name resolution, respectively. TCP shows significant usage, reflecting its role in reliable communication for applications like HTTP and email, while UDP, though lower, supports lightweight and latency-sensitive applications such as video streaming. TLS and HTTP have relatively low occurrences, indicating limited secure traffic or browsing activity. The chart reveals a mix of communication, resolution, and secure protocols, offering insights for optimizing resource allocation and enhancing network security.

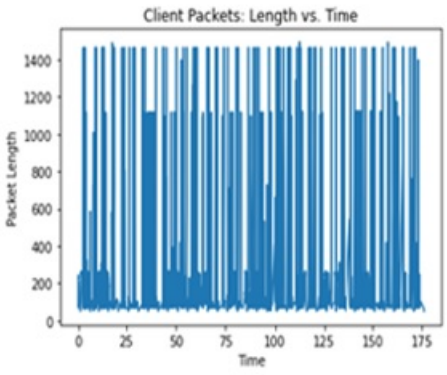

Figure – 3 (a) Client Packets

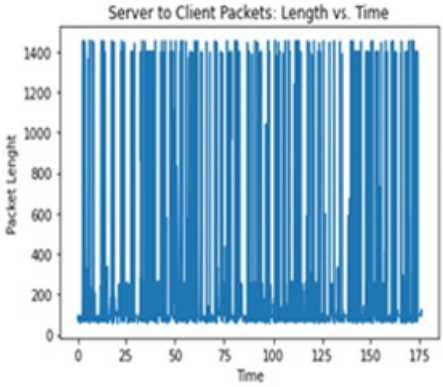

Figure – 3 (b) Server to Client Packets

Figure 3(a) illustrates the relationship between packet length and time for client-to-server transmissions in a local area network (LAN). The packet lengths range from 200 bits to 1400 bits, with frequent occurrences of shorter packets, indicating lightweight operations such as DNS lookups. Occasional spikes to the maximum packet length (~1400 bits) suggest data-heavy operations like file uploads. In contrast, Figure 3(b) represents server-to-client transmissions, where packets also range between 200 bits and 1400 bits. However, server packets exhibit a higher frequency of maximum-length packets, reflecting bulk data transfers or file downloads. Shorter packets interspersed with larger ones likely correspond to acknowledgments or control messages.

5.1 Network Traffic Classification Analysis

The Logistic Regression model (Xiaonan, Yon, Zhewen, & Kaiyuan, 2019) achieved an impressive overall accuracy of 99.92% in classifying six network traffic types: File Sharing, Instant Message, Video, Voice OverIP, Email, and P2P. Most classes, including Instant Message, Video, Voice Over IP, and Email, demonstrated perfect precision, recall, and F1-scores, reflecting flawless classification.

```
Confusion matrix:
 [[  46    0    0    0    0    0]
 [   0 1677    0    0    0    0]
 [   0    0    7    0    0    0]
 [   0    0    0    4    0    0]
 [   0    0    0    0  840    0]
 [   2    0    0    0    0   30]]
                precision    recall  f1-score   support

   FileSharing       0.96      1.00      0.98        46
InstantMessage       1.00      1.00      1.00      1677
         Video       1.00      1.00      1.00         7
   VoiceOverIP       1.00      1.00      1.00         4
         email       1.00      1.00      1.00       840
           p2p       1.00      0.94      0.97        32

   avg / total       1.00      1.00      1.00      2606

   Accuracy Score: 0.9992325402916347
```

Figure – 4 Logistic Regression Model

File Sharing achieved high scores with a precision of 0.96 and an F1-score of 0.98, while P2P traffic showed minor misclassification, with a recall of 0.94 and an F1-score of 0.97. The confusion matrix indicates

only two misclassified instances, emphasizing the model's reliability. This exceptional performance underscores the suitability of Logistic Regression for network traffic classification, particularly in datasets with well-defined and distinct traffic categories, providing robust support for efficient network management and security (Goyal, et al.).

```
Confusion matrix:
 [[  42    4    0    0    0    0]
 [   0 1677    0    0    0    0]
 [   0    0    7    0    0    0]
 [   0    0    0    4    0    0]
 [   0   14    0    0  826    0]
 [   0    0    0    0    0   32]]
                precision    recall  f1-score   support

    FileSharing       1.00      0.91      0.95        46
InstantMessage       0.99      1.00      0.99      1677
         Video       1.00      1.00      1.00         7
   VoiceOverIP       1.00      1.00      1.00         4
         email       1.00      0.98      0.99       840
           p2p       1.00      1.00      1.00        32

   avg / total       0.99      0.99      0.99      2606

 Acc= 0.9930928626247122
```

Figure – 5 Support Vector Machine (SVM) model

The Figure – 5 shown that Support Vector Machine (SVM) model [30] demonstrated outstanding performance in classifying six types of network traffic—File Sharing, Instant Message, Video, Voice OverIP, Email, and P2P—achieving an overall accuracy of 99.30%. Most traffic types, including Instant Message, Video, Voice OverIP, and P2P, showed near-perfect precision, recall, and F1-scores, indicating exceptional classification accuracy. File Sharing and Email traffic had minor misclassifications, with four and 14 instances misclassified, respectively, resulting in slightly lower recall scores of 0.91 and 0.98. Despite these minor errors, the model's high precision and recall across all categories highlight its robustness and effectiveness in managing well-defined network environments. These results underscore SVM's suitability for efficient resource allocation and enhanced network security in diverse and complex traffic.

Figure 6 visualized that the K-Nearest Neighbors (KNN) model achieved an impressive overall accuracy of 99.92% in classifying six types of network traffic: File Sharing, Instant Message, Video, Voice OverIP, Email, and P2P. Most traffic types, including Instant Message, Video, Voice OverIP, and Email, demonstrated perfect precision, recall, and F1-scores, reflecting flawless classification. File Sharing showed high recall (1.00) with a precision of 0.96 and F1-score of 0.98, while P2P traffic had minor misclassifications, with two instances incorrectly classified, resulting in a recall of 0.94 and F1-score of 0.97. The model's ability to handle distinct traffic categories with minimal errors highlights its robustness and suitability for network traffic classification.

```
Confusion matrix:
 [[  46    0    0    0    0    0]
 [   0 1677    0    0    0    0]
 [   0    0    7    0    0    0]
 [   0    0    0    4    0    0]
 [   0    0    0    0  840    0]
 [   2    0    0    0    0   30]]
                precision    recall  f1-score   support

    FileSharing       0.96      1.00      0.98        46
InstantMessage       1.00      1.00      1.00      1677
         Video       1.00      1.00      1.00         7
   VoiceOverIP       1.00      1.00      1.00         4
         email       1.00      1.00      1.00       840
           p2p       1.00      0.94      0.97        32

   avg / total       1.00      1.00      1.00      2606

   Accuracy Score: 0.9992325402916347
```

Figure 6 K-Nearest Neighbors (KNN) model

This performance confirms KNN as a reliable tool for efficient network management, resource allocation, and enhancing network security (Goyal, et al.).

Table 1: Comparison of Logistic Regression, SVM, and KNN Models

Model	Overall Accuracy	Perfectly Classified Traffic Types	Strengths
Logistic Regression	99.92%	Instant Message, Video, Voice OverIP, Email	High accuracy, simple implementation, reliable for well-defined datasets, suitable for network security and resource management.
Support Vector Machine (SVM)	99.30%	Instant Message, Video, Voice OverIP, P2P	Exceptional handling of complex traffic patterns, robust precision and recall, effective in diverse environments.
K-Nearest Neighbors (KNN)	99.92%	Instant Message, Video, Voice OverIP, Email	Reliable for distinct traffic categories, adaptable to well-separated datasets, suitable for efficient network security.

Table 1 show that Logistic Regression and KNN both achieved the highest accuracy of 99.92%, outperforming SVM, which had an accuracy of 99.30%. All models demonstrated excellent performance on Instant Message, Video, Voice OverIP, and Email traffic (Joice & Selvi, 2025). Logistic Regression and KNN had minimal misclassifications (2 P2P instances each), whereas SVM showed higher misclassification rates, particularly for File Sharing and Email traffic. While Logistic Regression and KNN are better suited for datasets with clearly defined traffic categories, SVM excels in handling complex and diverse traffic patterns. This comparison highlights the strengths and weaknesses of each model, aiding in selecting the most appropriate approach for specific network traffic classification needs (Goyal, et al.).

6. CONCLUSIONS

This research demonstrates the transformative potential of advanced machine learning techniques for network traffic classification, addressing the challenges posed by modern, dynamic traffic patterns. The models evaluated—Logistic Regression, Support Vector Machines (SVM), and K-Nearest Neighbors (KNN)—exhibited exceptional classification performance, achieving overall accuracies of 99.92% for Logistic Regression and KNN, and 99.30% for SVM. Logistic Regression and KNN proved particularly effective for datasets with clearly defined traffic categories, while SVM excelled in handling complex and diverse traffic patterns. All three models showed outstanding results in classifying traffic types such as Instant Message, Video, VOIP, and Email, with minimal misclassifications observed in File Sharing and P2P traffic. These findings highlight the robustness and adaptability of these algorithms for real-world applications, enabling efficient resource allocation, congestion control, and anomaly detection. Furthermore, the integration of advanced preprocessing, feature extraction, and evaluation metrics underscores the importance of systematic workflows in achieving reliable classification outcomes.

The research underscores the critical role of machine learning in advancing network management, offering scalable solutions to meet the demands of data-intensive environments while ensuring security and operational efficient (Goyal, et al.). Future work can focus on enhancing model performance by incorporating hybrid models, optimizing feature selection, and addressing evolving traffic patterns in increasingly complex networks. This study provides a robust foundation for leveraging machine learning in network management, fostering innovation, and supporting intelligent and secure network operations.

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Applications of Natural Gamma Ray Spectrometry Tool for Petrophysical Analysis of Hydrocarbon Reservoir in Oil & Gas Industry

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Abstract: Gamma ray tool used for petrophysical analysis in Oil & Gas industry is for natural radioactivity in rocks in subsurface. Potassium (^{40}K), uranium (^{236}U) and thorium (^{232}Th) are three decay series of isotopes are abundant in rocks and are detected by Natural Gamma Ray Spectrometry (NGS) tool. Potassium, thorium and uranium spectra of Gamma ray is obtained by NGS tool with NaI crystal of photo multiplier tube. NGS tool has five windows for counting the gamma rays of low energy and high energy level. Tool has a master calibration in Clamart (France). Secondary calibrators are used to check the operation of the tool and its stability. Natural Gamma Ray Spectrometry measures the contribution of gamma ray of each individual series of Thorium, Uranium and Potassium separately. Also, it measures concentration of Thorium and Uranium in ppm and potassium in percentage in any rock. Applications of NGS are many folds. This is very good shale indicator. Also, it differentiates between shale and potassium salts (Evaporites) with help of cross plots of K% versus bulk density, neutron porosity and sonic transit time. From the ratio of Th/K obtained from NGS tool against rocks, it distinguishes feldspathic sandstone, micaceous sandstone or quartzite sandstone. Feldspar contain high potassium and low thorium as a result Th/K ratio is very low against Feldspathic sandstone whereas the ratio is high in Micaceous sandstone due to high thorium in mica and low potassium. NGS tool play an important role to find the origin of carbonate either in pure chemical origin or organic by measuring the uranium. Low uranium indicates it is of chemical origin whereas rich content of uranium in carbonate indicates it is reducing environment and of organic origin. NGS also shows Th/K ratio abruptly high in case of unconformities. It is possible to find the organic content from measurement of uranium and from that its hydrocarbon potential in source rock after proper calibration with core data.

Key words: Shale and Evaporite, Carbonate series, Th/K ratio, Unconformity, Organic matter and Uranium concentration,

1. INTRODUCTION

Two types of Gamma ray tool are available in Oil industry. One is conventional Gamma ray tool and other is Natural Gamma ray Spectrometry (NGS). Conventional Gamma ray tool measures the total gamma ray but could not recognize the contribution of gamma ray of individual series of potassium, thorium and uranium separately. This is the ambiguity of normal Gamma Ray tool. This ambiguity is removed by Natural Gamma Ray Spectrometry (NGS) tool. It measures the contribution of gamma ray of each individual series of isotopes. Also, it measures concentration of Thorium and Uranium in ppm and potassium in percentage in any rock.

NGS tool in well logging industry is known as Lithology tool and it has many applications in petroleum industry**.** It identifies evaporating minerals and distinguishes it from shale as evaporating minerals contain more concentration of potassium than that of shale. NGS also identify type of sandstone whether it is feldspathic, micaceous or mixed. Detection of unconformities by NGS tool is another advantage for exploration of hydrocarbon. Depositional environment of Carbonate rock origin either in organic or inorganic and its source rock finding after measuring the percentage of organic matter through uranium concentration by NGS tool is another milestone in exploration business of oil industry.

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2. ORIGIN OF NATURAL RADIOACTIVITY IN ROCKS AND GAMMA RAY EMISSION SPECTRA

The isotopes of short life time disappear long ago but there are some radio isotopes in rocks having a sufficient long life and they disintegrate GR which have discrete energy levels. Potassium (^{40}K) is an isotope (half-life is 1.3 x 10^9 years) which is abundant in sedimentary rocks of Shale and Evaporites. Uranium (^{238}U) is another isotope (half-life is 4.4 x 10^9 years) found in sandstone and specially in organic Limestone. Thorium (^{232}Th) isotope (half-life is1.4 x 10^9 years) is found in monazite sand. Due to geological processes this natural radioactive isotopes are abundant in rocks within the earth's crust.

Potassium ^{40}K disintegrate to give Argon ^{40}A which is stable after emitting Gamma radiation of energy single spectrum of 1.46 Mev (figure 1). For Uranium and Thorium series, the process is more complex which gives a series of isotope some of which are gamma ray emitters. Thorium – 232 and Uranium – 238 decay series are not discussed here.

The conventional gamma ray tool lowered in borehole for petrophysical analysis is having limited option. The natural gamma radiation (counts per second or in API unit) from rocks below the surface is combination of total radiated gamma ray emitted from K ^{40}, Th ^{232} & U ^{238} series. The disadvantage of conventional gamma ray tool is that it cannot detect separately Gamma ray counts from each individual series of Potassium, Uranium and Thorium. Also, it is not able to quantify the presence of individual quantity of potassium, thorium and uranium in rocks. These demerits of conventional Gamma radiation tool are removed by 'Natural Gamma Ray Spectrometry' tool which can identify Gamma radiations from each of three decay series and quantify the amount of Thorium (Th) & Uranium (U) in ppm (parts per million) and potassium (K) in percentage within the rock below surface at any depth within a borehole.

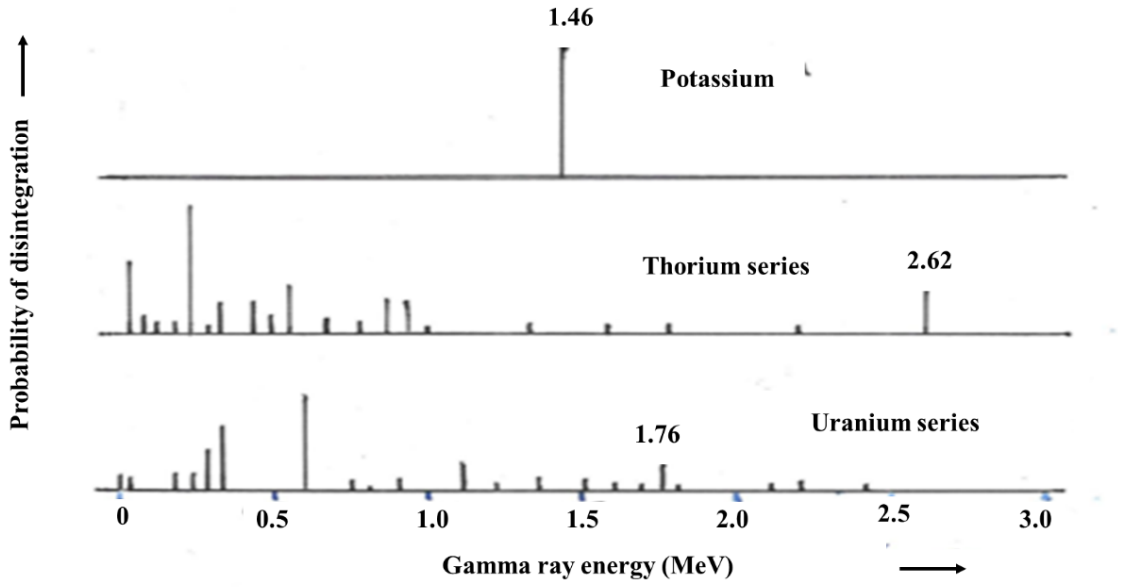

Figure 1: Gamma Ray emission Spectra of three Radioactive decay series (courtesy of Schlumberger)

Figure1 is showing the discrete energy level of gamma ray radiated. K^{40} is having single gamma radiated by 1.46 MeV from Ar ^{40} isotope. Th ^{232} is characterized by so many gamma radiations from their decay products in which Thallium (^{208}TI) emits GR whose energy is 2.62 MeV. U^{232} is another decay series of uranium in which Bismuth (^{214} Bi) emits GR at 1.76 MeV.

The detector has an intrinsic resolution broadening the picks. The observed continuous spectrum is shown in figure 2. The amplitudes of the three spectra will depend on radioactive components present so that a quantitative evaluation of Th, U and K can be found out. In the spectrum there are two regions:

1. High energy region – it is concerned with picks of 2.62 MeV from thorium series, 1.76 MeV energy level from Uranium decay series and 1.46 MeV from Potassium.
2. Low energy region – it is the concerned with of pair production and Compton scattering in the rock itself plus lower energy GR radiation from 2 decay family namely Thorium and Uranium decay series.

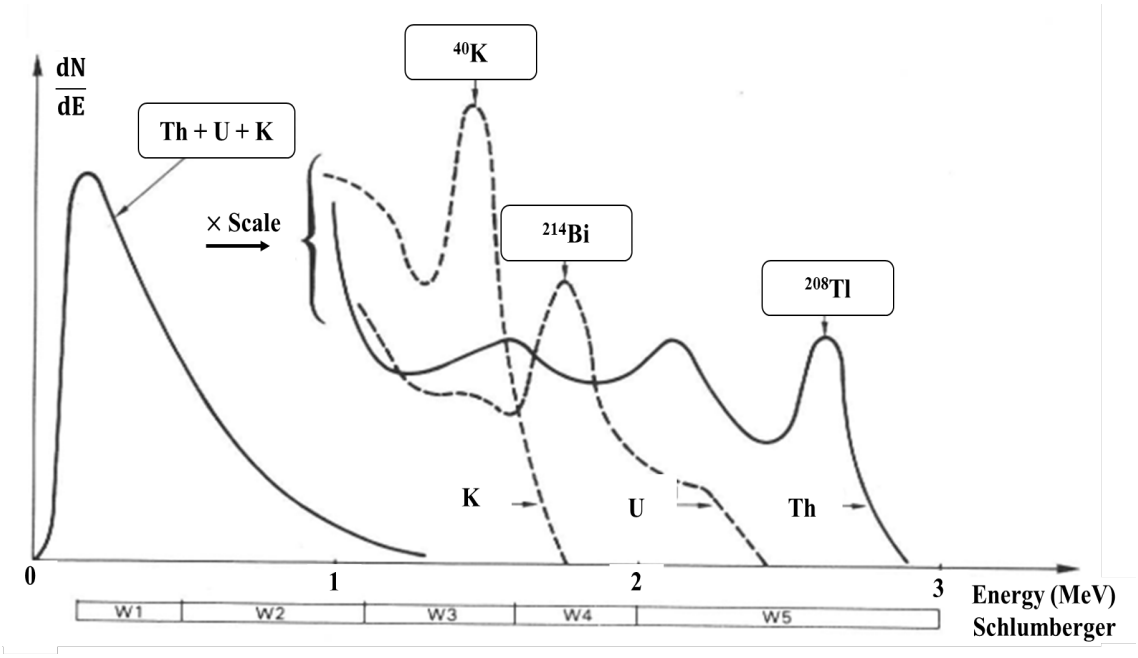

Figure 2: Potassium, Thorium and Uranium response curve with the NaI crystal detector position of the windows. (from Serra et al,1980)

3. EVAPORATING ENVIRONMENT

Evaporite minerals and shales both contain potassium. But there is a distinct difference between them. Evaporites has much higher concentration of potassium than that of clay minerals in shales. No thorium content in evaporite as thorium is insoluble (Clark, S.P., Peterman, Z.E. and Heier, K.S 1966). Therefore, against Evaporites, Th-curve would be flat or almost zero while K-curve has higher percentage of Potassium and Uranium curve is nearly zero. Against shale K-curve would be high but not so high as observed in Evaporite minerals. Figure 3 is well log data of NGS -Litho Density -Neutron porosity of well X of ONGC, India. NGS shows a very good distinguishable of Shale and Evaporite.

Figure 3 shows that the depth interval of log motif from 4045- 4048 feet, Gamma Ray (GR) curve in the first track is nearly 60 API, Thorium (Th) and Uranium (U) in 2nd track are 4 and 2 ppm respectively and Potassium(K) in 2nd track is 2% whereas in depth interval 4063- 4065 ft, the GR-curve is showing 165 API, Th is 2ppm, U is nearly zero and K > 10% which gives an indication of evaporite mineral. From log data and cutting samples while drilling in a well X of ONGC, India tells us that the interval 4045-4048 feet is shale whereas the interval 4063 -4065feet is Potassium salts (Sylvite). Due to presence of high content of potassium in the interval 4063-4065 feet, Gamma ray is showing high.

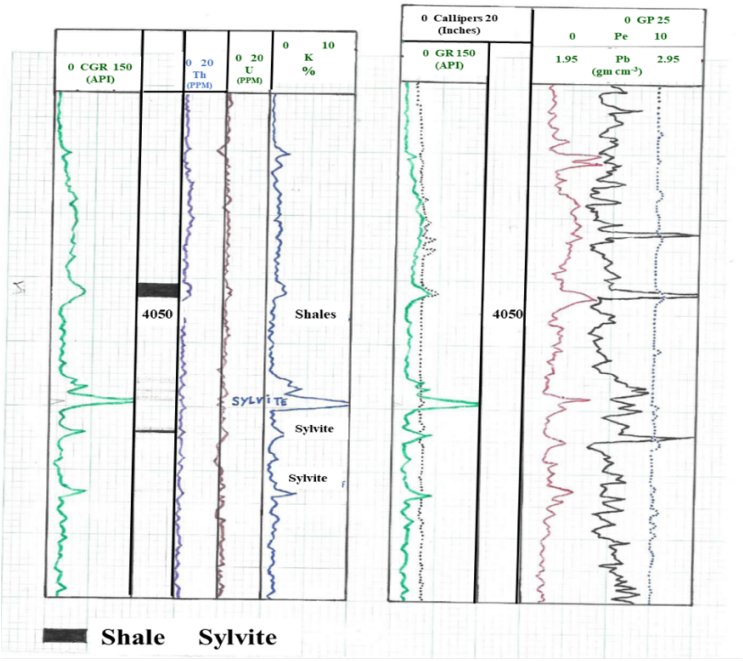

Figure 3 shows NGS response in an evaporitic interval of well X of ONGC well, India

Table 1: showing different types of Potassium minerals of Evaporites obtained by courtesy of Schlumberger.

NAME	COMPOSITION	K (% wt)	P_b (g/cm^3)	P_e (b/e)	Φ_n (%)	Δt (μs/ft)
Sylvite	KCl	52.44	1.86	8.51	- 3	74
Langbeinite	$K_2SO_4\,(MgSO_4)_2$	18.84	2.82	3.56	- 2	52
Kainite	$MgSO_4$, KCl, $(H_2O)_3$	15.7	2.12	3.5	> 60	
Carnallite	$MgCl_2$, KCl, $(H_2O)^6$	14.07	1.57	4.09	> 60	83
Polyhalite	K_2SO_4, $MgSO_4$, $(CaSO_4)$, $(H_2O)_2$	13.37	2.79	4.32	25	5.75
Glaserite	$(KNa)_2$, SO_4	24.7	2.7			

K- Potassium, P_b - Bulk density, P_e - Photo electric coefficient, Φ_n - Neutron Porosity, Δt - Sonic transit time.

Table1 is showing different types of evaporite minerals with K (% wt). If these evaporites are sufficiently thick beds, K-curve in NGS log will be nearly exact values as shown in the Table 1.

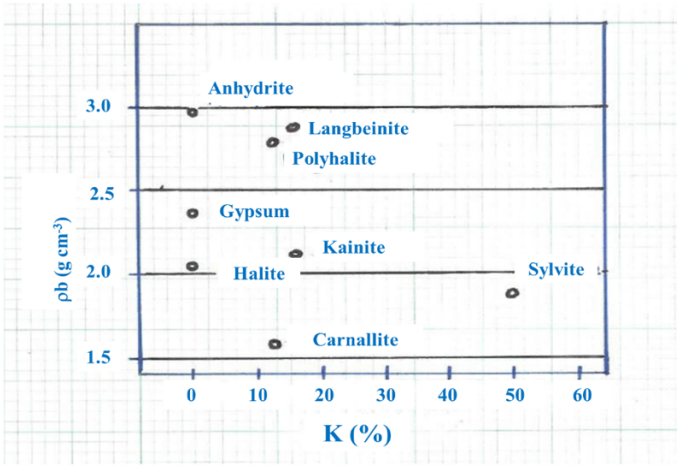

Figure 4.a: Cross plot technique of Potassium (K) versus Bulk density (ρb) to determine evaporite minerals

Otherwise, we should run NGS tool with Litho Density (P_b), Neutron porosity (Φ_n) and Sonic (ΔT) for detection of evaporites. Cross plot between P_b versus K%, Φ_n versus K% and Δt versus K% are sufficient to distinguish the type of evaporate. (Figure 4a, b, c).

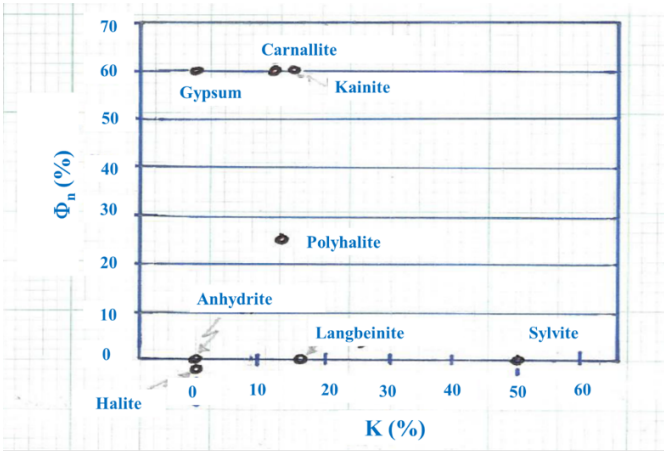

Figure 4 b: Cross plot technique of Potassium (K) versus Neutron porosity (φ_n) to determine evaporite minerals

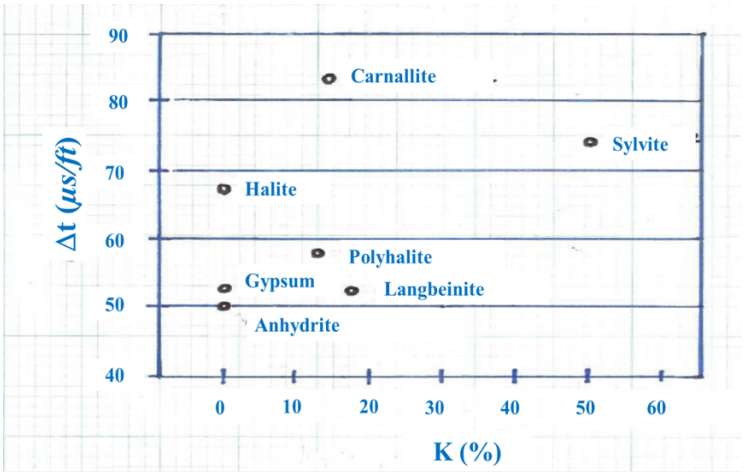

Figure 4.c: Cross plot technique of Potassium (K) versus Sonic Transit Time (DT) to determine evaporite minerals.

4. SAND SHALE SERIES/CARBONATE SHALE SERIES

Pure sandstone for log analysis is considered to be quartz in which clay minerals percentage is less than 5% as a result presence of Potassium (K), Thorium (TH) and Uranium (U) in pure sandstone are very low due to which gamma ray activity in pure sandstone is very low. From GR curve against sandstone showing very low, it is considered to be that grains presence in sandstone are coarse grains sizes and they are well sorted, chemically and texturally matured of detrial origin. On the other hand, pure shales are just opposite in which GR activity is high. NGS tool identifies that GR activity in shale is high due to presence of high concentration of Potassium as clay minerals are present in shale. But sometimes it is observed that sandstone also shows high radioactivity of GR. From depositional environment of sedimentology, it is observed that some clay minerals are also present in sandstone and log analysist called them Shaly-sand. Feldspathic sandstone or Micaceous sandstone also contain good amount of Potassium minerals due to which radioactivity of GR exist in those types of sandstone. Also, monazite sandstone found in beach area are having thorium minerals which shows high GR activity. NGS tool specifically identified Thorium and Uranium in ppm and Potassium in percentage and therefore, are able to identify the origin of radioactivity from which it is easier to interpret the lithological analysis.

From ordinary GR tool, volume of shalyness or shale indicator is as follows:

$$(V_{sh})_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \times 100 \quad (1)$$

But this shale indicator could not speak about the individual presence of Uranium, thorium or Potassium and therefore, it was difficult task to interpret the lithology. But now good shale indicators obtained from NGS tool are as follows:

$$(V_{sh})_{Th} = \frac{Th - Th_{min}}{Th_{sh} - Th_{min}} \quad (2)$$

$$(V_{sh})_{K} = \frac{K - K_{min}}{K_{sh} - K_{min}} \quad (3)$$

$$(V_{sh})_{CGR} = \frac{CGR - CGR_{min}}{CGR_{sh} - CGR_{min}} \quad \text{[CGR is combination of Th and K]} \quad (4)$$

It is clear that $(V_{sh})_{Th}$, $(V_{sh})_{K}$, $(V_{sh})_{CGR}$ are good Shale indicator because now individual Th, U, and K can be obtained from which we can interpret lithology.

4.1 Carbonate - Shale Series

Figure 5 presents the NGS log data of a well Y, India which display the three curves. Blue continuous curve is the counts of Gamma rays radiated from Thorium series, black dash line curve is the Gamma ray counts radiated from combination of the Thorium and Potassium series and the pink continuous curve represents the total Gamma ray counts radiated from combination of Thorium, Uranium and Potassium. The intervals marked in figure 5 are shales and dolomites. Against shale it is observed that potassium is very high due to presence of clay minerals in shales whereas Uranium is very low. Against Dolomite bed, it is observed that Uranium is very high and Potassium is low. Uranium high may be due to organic carbon or presence of phosphatic minerals.

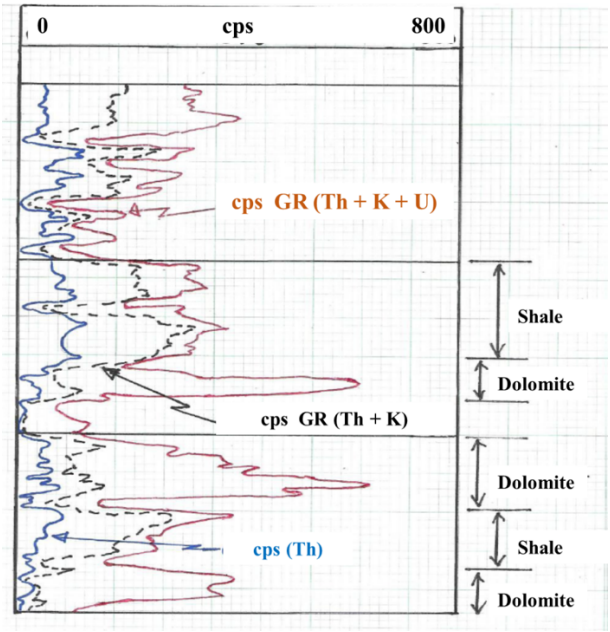

Figure 5: Formation response due to Thorium, Thorium & Potassium, Thorium-Potassium-Uranium of NGS data of well Y, India

4.2 Sand Shale series

Table 2 showing potassium bearing minerals in sand-shale series

Name		Chemical Formula	K content (% weight)
○ FELDSPARS			
	Microcline	$KALSi_3O_8$	16 to 11
Alkali	Orthoclase	$KALSi_3O_8$	14 to 12
	Anorthoclase	$(Na,K)\ ALSi_3O_8$	
○ MICAS			
Muscovite		$KAL_2(ALSi_3O_{10})\ (OH,F)_2$	10 to 8
Biotite		$K(Mg,Fe)_3(ALSi_3O_{10})\ (OH,F)_2$	6 – 10
Illite		$K_{1-1.5}Al_4\ (Si_{7-6.5}\ AL_{1-1.5})O_{20}\ (OH)_4$	3.5 – 8
Glauconite		$K_2(Mg,Fe)_2AL_6(Si_4O_{10})_3(OH)_{12}$	3.2 – 5.8
Phlogopite		$KMg_3(ALSi_3O_{10})(F,OH)_2$	6.2 – 10
○ FELDSPATHOIDS			
Metasilicates	Leucite	$KAL\ (SiO_3)_2$	17.9
Orthosilicates	Nephelite	$(Na,K)\ ALSiO_4$	4 to 8
○ OTHER CLAY MINERALS*			
Montmorillonite			0 –4.9
Chlorite			0 – 0.35
Kaolinite			**0 – 0.6**

4.2.1 Feldspathic Sand stone

If sandstone contains minerals of microcline, orthoclase, Anorthoclase in certain percentages which are Feldspathic minerals (Table 2), then this type of sandstone is called Feldspathic Sandstone. Feldspathic sandstone can be distinguished from the ratio of Th/K (Figure 6 and table 2)**.** As Potassium is very high in feldspar and Thorium is low, the ratio of Th/K is very low in the order of $1x10^{-4}$ as shown in figure 6.

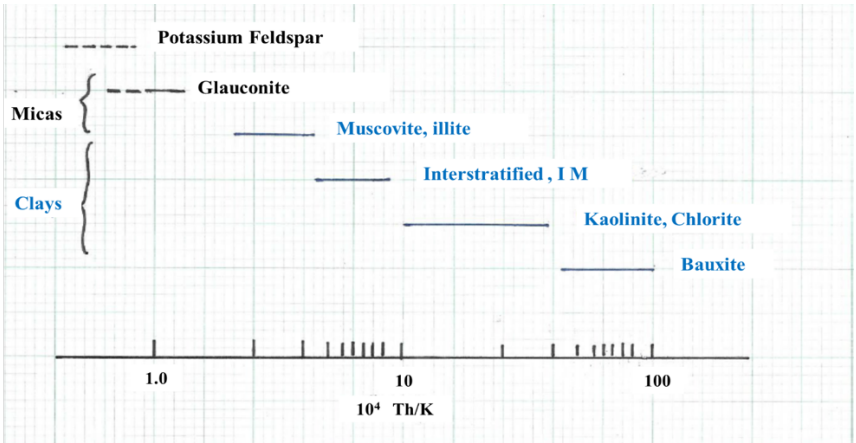

Figure 6: Mineralogical identification by the Th/K ratio given by NGS tool (from Hassan & Hossin, 1975)

4.2.2 Micaceous Sandstone

Micas contain potassium and percentage of K in potassium bearing minerals in Micaceous sandstone is comparatively lower than Feldspathic sandstone as shown in table 2. Th content in micas is higher as a result Th/K ratio is higher in Micaceous sandstone than in comparison to Feldspathic sandstone and it is in the order of 2.5x 10^{-4} shown in figure 6.

5. CARBONATE SERIES

Two types of carbonate rock are found in sedimentary rocks. One is chemical origin and other is organic.

Chemical origin of carbonate: If carbonate is of chemical origin, then thorium could not be present in carbonate because thorium is insoluble. If NGS log shows that Thorium is flat and nearly zero, and also potassium is flat, then this carbonate is pure carbonate. Also, if NGS log shows that it is Uranium free, then it is considered that pure carbonate is precipitated in oxidizing environment and therefore it is of chemical origin.

Organic origin of carbonate and source rock: If NGS shows that uranium is having variable percentages against carbonate rock, it indicates that carbonate is deposited in reducing environment favorable to organic matter and therefore, this carbonate is of organic origin and chance of organic matter converted into Kerogen and later under pressure and temperature transformed into hydrocarbon. If Th and K are present with U, this indicates the presence of Clay in the carbonate rock. So, carbonate as a source rock can be found out from NGS log data and also the depositional environment can be found out. Figure 7 is NGS log motif of well A, India showing radioactivity of GR is due to mainly presence of uranium in carbonate series. Through the interval, Thorium and Potassium are flat or nearly zero, but uranium in ppm is very high above 90 mts in carbonate series. CGR is counts of GR radiated from Thorium & Potassium series.

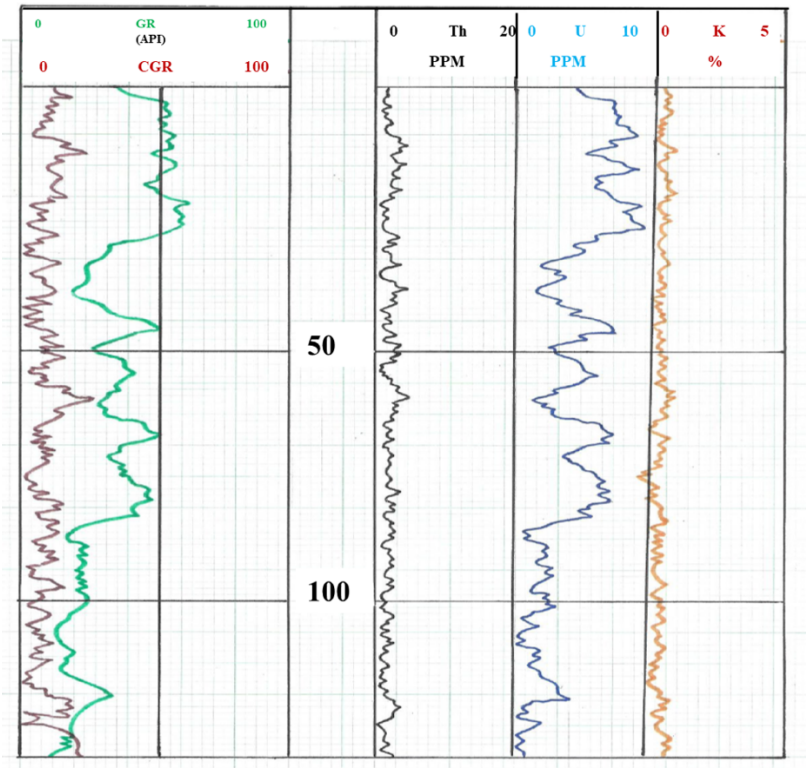

Figure 7: NGS in Carbonate series showing that radioactivity is mainly due to Uranium of well A, India

6. NGS LOG HELPS TO IDENTIFY UNCONFORMITIES

Conventional logs like resistivity, SP, Density, Neutron porosity and Sonic could not identify the unconformities as shown in figure 8. Micro resistivity image tool can alone identify unconformities from its dip direction which changes abruptly. But this tool is very costly. NGS tool can identify easily if Th/K ratio log is carried out. There is a abrupt changes of Th/K ratio against unconformities. Figure 8 is the log motif of well Z, India showing that the interval below 3900 m is unconformities as ratio of Th/K is abruptly high below the interval 3900m.

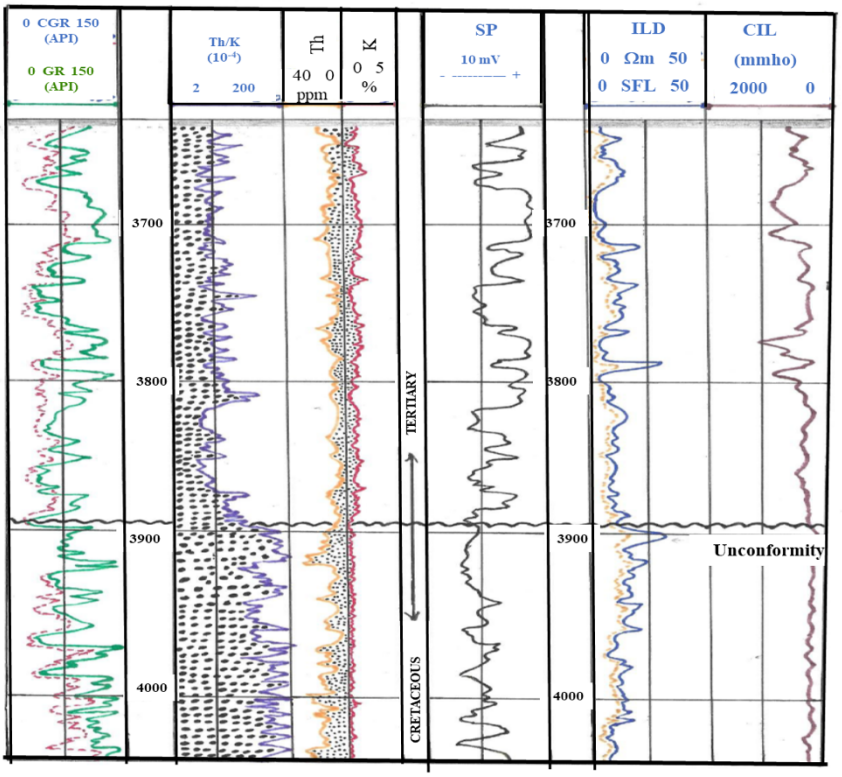

Figure 8 Unconformity identified by NGS tool and not seen by other logs of well Z, India

7. HYDROCARBON POTENTIAL

It is observed that there is a relation between organic matter and Uranium content. If we do calibration with core sample, then estimation of organic matter content of source rock from its uranium content and from that Hydrocarbon potential can be found out (Figure 9 A and 9 B).

Point a in both figure 9 A and 9 B is on the line of 75 percent Humic, 25 percent Sapropelic. From the coordinate of **point a** in figure 9 A, it indicates that total organic matter is 25% and Uranium is 0.0064 %. The same **point a** in figure 9 B yields 7.0 gallons oil per ton.

Point b in both figure 9 A and 9 B is on the line of 25 percent Humic, 75 percent Sapropelic. From the coordinate of **point b** in figure 9 A, it indicates that total organic matter is 25% and Uranium is 0.0027 %. The same **point b** in figure 9 B yields 12.3 gallons oil per ton.

Point c in both figure 9 A and 9 B is on the line of 50 percent Humic, 50 percent Sapropelic. From the coordinate of **point c** in figure 9 A, it indicates that total organic matter is 20% and Uranium is 0.0036 %. The same **point c** in figure 9B yields 7.6 gallons oil per ton.

Point c$^{/}$ in both figure 9 A and 9 B is on the line of 50 percent Humic, 50 percent Sapropelic. From the coordinate of **point c$^{/}$** in figure 9 A, it indicates that total organic matter is 30% and Uranium is 0.0055 %. The same **point c$^{/}$** in figure 9 B yields 11.6 gallons oil per ton.

From the above graphs mentioned in Figure 9 A and 9B we can infer as follows:

1. Uranium percent increases with increase of total organic matter.
2. Oil yield also increases with increase of total organic matter.
3. Uranium percent is high if Humic in percentage is more than Sapropelic in total organic matter.
4. Oil yield is high if Sapropelic in percentage is more than Humic in total organic matter.

From the above discussion, it can be said that uranium content from NGS log can evaluate the total organic matter of the source rock and from those yields of hydrocarbon and its potential.

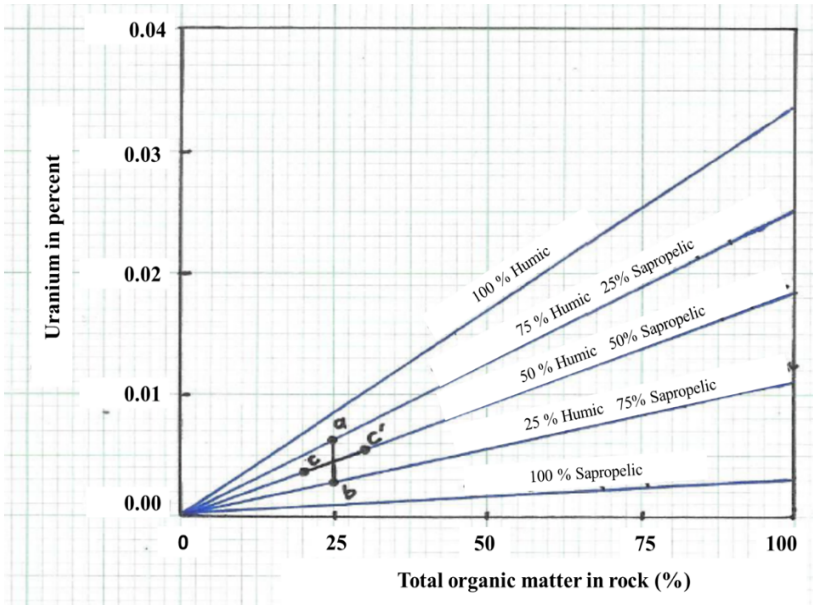

Figure 9 A: Uranium percent versus total organic matter of a black marine shale which contains organic matter in proportions of Humic and Sapropelic material (from Swanson,1960)

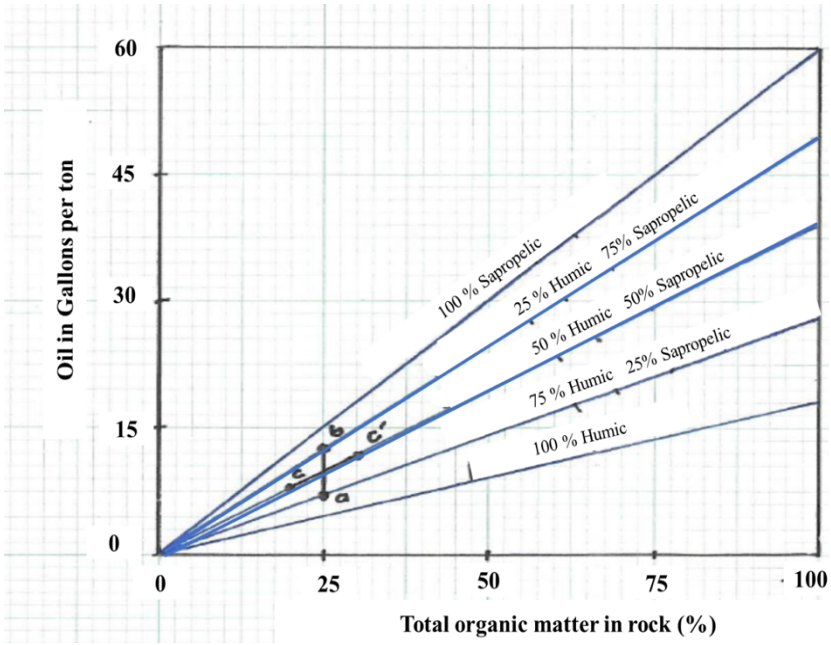

Figure 9 B: Oil yield versus total organic matter in percent of a black marine shale which contains organic matter in proportions of Humic and Sapropelic material (from Swanson 1960)

8. DISCUSSION AND CONCLUSIONS

Gamma ray high in geological bed does not mean that it is shale. The log data in Figure 5 shows that in Dolomite bed Uranium is high, Potassium is low. Uranium in dolomite bed is high due to presence of organic carbon or phosphatic minerals. Also, it is observed that Uranium is flat or nearly zero and potassium is very high in shale bed. Thus NGS is able to distinguish reservoir and non-reservoir rock.

NGS distinguishes between shale and potassium salts (Evaporites). Both of them contain potassium but in evaporites, potassium percentage are very high. Cross plots of bulk density (ρ_b) versus K%, Neutron porosity (Φ_n) versus K% and Sonic transit time (DT) versus K% are sufficient to identify the potassium salts (Figure 4a, 4b and 4c).

Log data of well Z of India is obtained as Induction log deep/Spontaneous Potential /Thorium/Potassium/ CGR/Total Gamma ray within certain interval. These petrophysical data are not able to find unconformity. But when we have plotted Th/K ratio in a particular track, it is observed that the ratio of Th/K is abruptly high below the depth of 3900 m which indicates that depth interval below 3900 m is a zone of Unconformity (Figure 8). Therefore, NGS plays an important role to identify the unconformity which is very cost effective as NGS tool is comparatively cheaper than Dip Meter tool such as Micro Resistivity Imager tool which shows sudden change of dip magnitude and dip azimuth of geological beds called Unconformity.

Core sample of source rock is obtained from black marine shale of one well. Calibration of core sample was carried out with uranium content and organic matter and from that hydrocarbon yield are obtained. It was found that oil yield is high if Sapropelic in percentage is more than Humic in total organic matter (Figure 9). This calibration of core sample can be used to find organic matter from uranium content obtained from NGS log and in turn oil yield of source rock.

Mineralogical identification within the rock is not obtained from conventional logging tools. But NGS plays a very important role for identify mineralogy of rocks. If the reservoir is sandstone, it can be understood from conventional tools but whether it is Feldspathic, Micaceous or quartzite that cannot be distinguished by logging tools except NGS. Th/K ratio obtained from NGS are used to identify lithology. As feldspar contains more potassium and very less thorium, so, the ratio of Th/K is very low indicating it is Feldspathic sandstone. In Micaceous sand, Potassium is low and thorium is comparatively high as a result Th/K ratio is high indicating that it is Micaceous sand (Figure 6).

Origin of Carbonate rock either it is pure chemical origin or organic, could not be found out from any logging tools except NGS. NGS tool has an application in sedimentology. Depositional environment of carbonate rock could be understood from uranium measurement. Free of uranium or very low percentage of uranium found in carbonate indicates oxidizing environment and therefore, carbonate is of pure chemical origin. If uranium found in carbonate is rich, it indicates deposition of carbonate in reducing environment and so carbonate is organic origin.

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Formation Evaluation of Hydrocarbon Reservoirs of Oil Fields in Geological Basin by the Help of Petrophysical Tools.

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Abstract: The purpose of formation evaluation is to identify the reservoir rock, evaluate the potential hydrocarbon and estimate the volume of those hydrocarbon reserves. Reservoir rock means it should be porous (void space) and permeable to get production of commercial volume of hydrocarbon. Petrophysical tools are to be lowered in the borehole to record continuous log data corresponding to depths within the borehole. Log data recorded from the tools are formation resistivity, resistivity of formation water of the reservoir, porosity, permeability, gamma ray log data for finding volume of shalyness etc. All these log data are used as inputs to the Special software of Electro Log Analysis (ELAN). Archie's equation for clean sand and Indonesian equation for shaly-sand are used in ELAN software for finding the water saturation in turn hydrocarbon saturation of the reservoir as an output. Also, effective porosity, volume of shalyness and matrix volume of the reservoir are displayed after ELAN processing.

Key words: Effective porosity, Volume of shalyness , Effective pay thickness, Secondary porosity, Water saturation

1. INTRODUCTION

Petrophysical tools lowered in the borehole for recording the continuous log data are resistivity tool along with spontaneous potential electrode, porosity tools and gamma ray tool. Resistivity of the formation can be found out from high resolution induction tool or Latero tools depending upon the type of fluids in the borehole. Induction tool is more favourable to the oil base mud and fresh water mud in the borehole whereas latero tools are more suitable in the borehole containing saline water bearing mud. For finding the porosity of the formation, we use at least two porosity tools such as litho density tool and neutron porosity tool. Litho density tool and neutron porosity tools are used to find the effective porosity and volume of shalyness of the reservoir rocks. Resistivity of formation water (R_w) can be found out from SP (spontaneous potential) log. Modular dynamic tester (MDT) is lowered against the reservoir rock in borehole and sample of formation water is collected and resistivity is measured on the surface. After giving temperature correction, the R_w can be determined exactly of the reservoir rock. The parameters *a* (Archie's constant), *m* (cementation factor) and *n* (saturation index) of particular field are found out from the core data in the core laboratory. After log data acquisition, it is processed by ELAN software to find water saturation in turn hydrocarbon saturation.

The effective pay thickness of the reservoir rocks and its area of cross-section can be found out from contour map of the particular reservoir of different wells of particular field. As we know the porosity (ϕ) and hydrocarbon saturation (S_{HC}), then the reserve of hydrocarbon can be estimated in a particular field. Here we will only concentrate about water saturation (S_w) in turn hydrocarbon saturation (S_{HC}), effective porosity (ϕ_e) and pay thickness of two different fields. One field is Sanand in Ahmedabad-Mehsana block of Cambay basin, India and another is the case history of one well log data interpretation of Indonesian field.

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2. OPEN HOLE LOG DATA & IT'S CHARACTERISTICS

Figure 1 is the log motif of triple combo (Resistivity – Density-Neutron and Gamma Ray). Gamma ray log in the interval 1397 – 1410 meter reads the value in the order of 15 to 20 API indicating that it is sand reservoir. SP is negative in back-up scale supporting gamma ray. The interval 1397- 1401 meter is very interesting where resistivity is showing 17 ohms meter which is comparatively high. In this interval density - neutron porosity curves are showing cross-over characteristics which indicates that the interval 1397-1401 meter is gas bearing sand. The interval 1401-1404 meter is showing resistivity gradient where resistivity values are decreasing from 10 ohm- meter to 2 ohm- meter from 1401 meter to 1404 meter which interprets that oil saturation is decreasing. Density - neutron porosity in this interval is very close to each other. Therefore, the interval 1401-1404 meter is called oil bearing zone. The interval 1404 - 1410 meter is showing resistivity value only 2 ohm-meter only throughout this interval. Density - neutron porosity curves are overlapping each other within this interval 1404 – 1410 meter. From the resistivity and density - neutron porosity curves, it is interpreted that the interval 1404 -1410 meter is 100% water saturation.

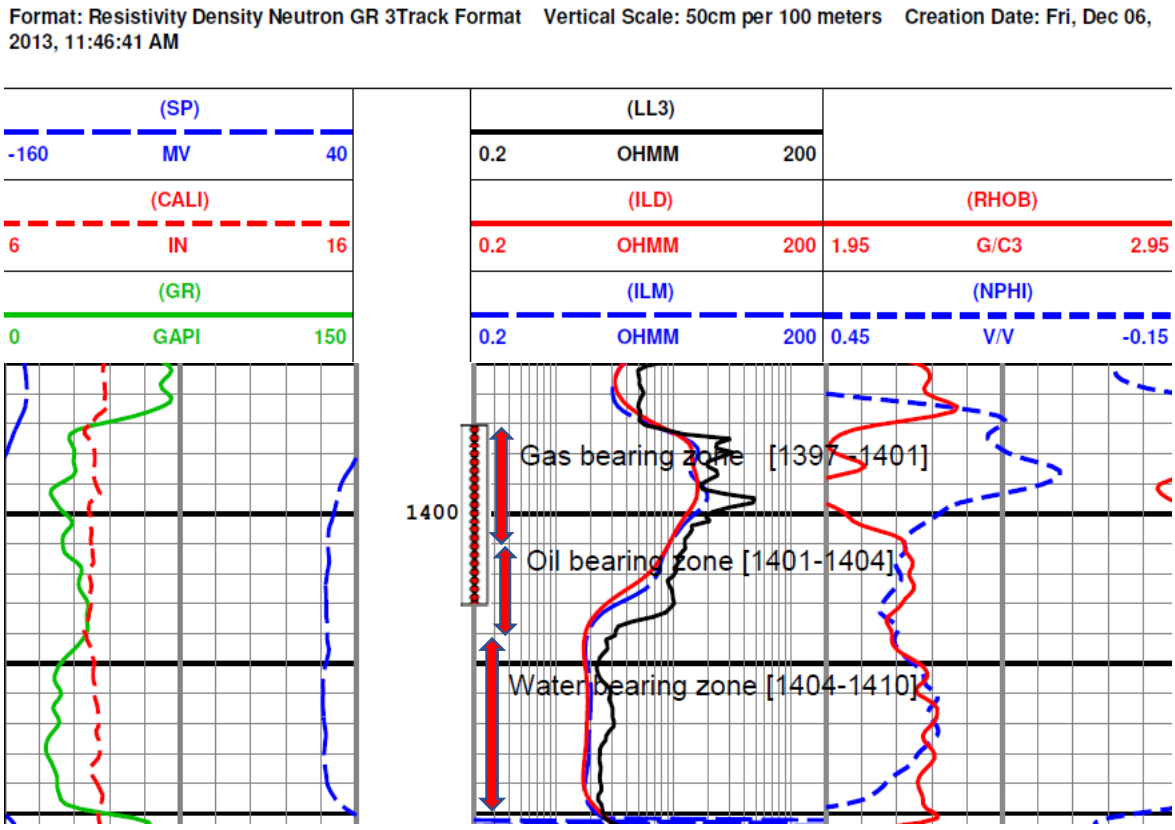

Figure 1: log motif of one well of ONGC-India showing cross-over between Density and neutron porosity in the interval 1397-1401 depicting gas reservoir characteristics. (Courtesy of ONGC, India 2013)

3. GEOLOGY OF CAMBAY BASIN, INDIA

The Cambay Basin in India is a proven hydrocarbon basin known for its thick tertiary sediments and significant shale gas potential. Cambay basin (figure 2) is located in North – West part of India, specifically within the West Indian state of Gujarat. It is an Intracratonic Rift Basin extending from Surat in the South to Sanchor in the North. Cambay Basin in the western part of India is divided into five tectonic blocks (figure 2). These blocks are separated by major cross faults. The five blocks are Narmada, Jambusar – Broach, Cambay – Tarapur, Ahmadabad – Mehsana and Patan – Sanchor.

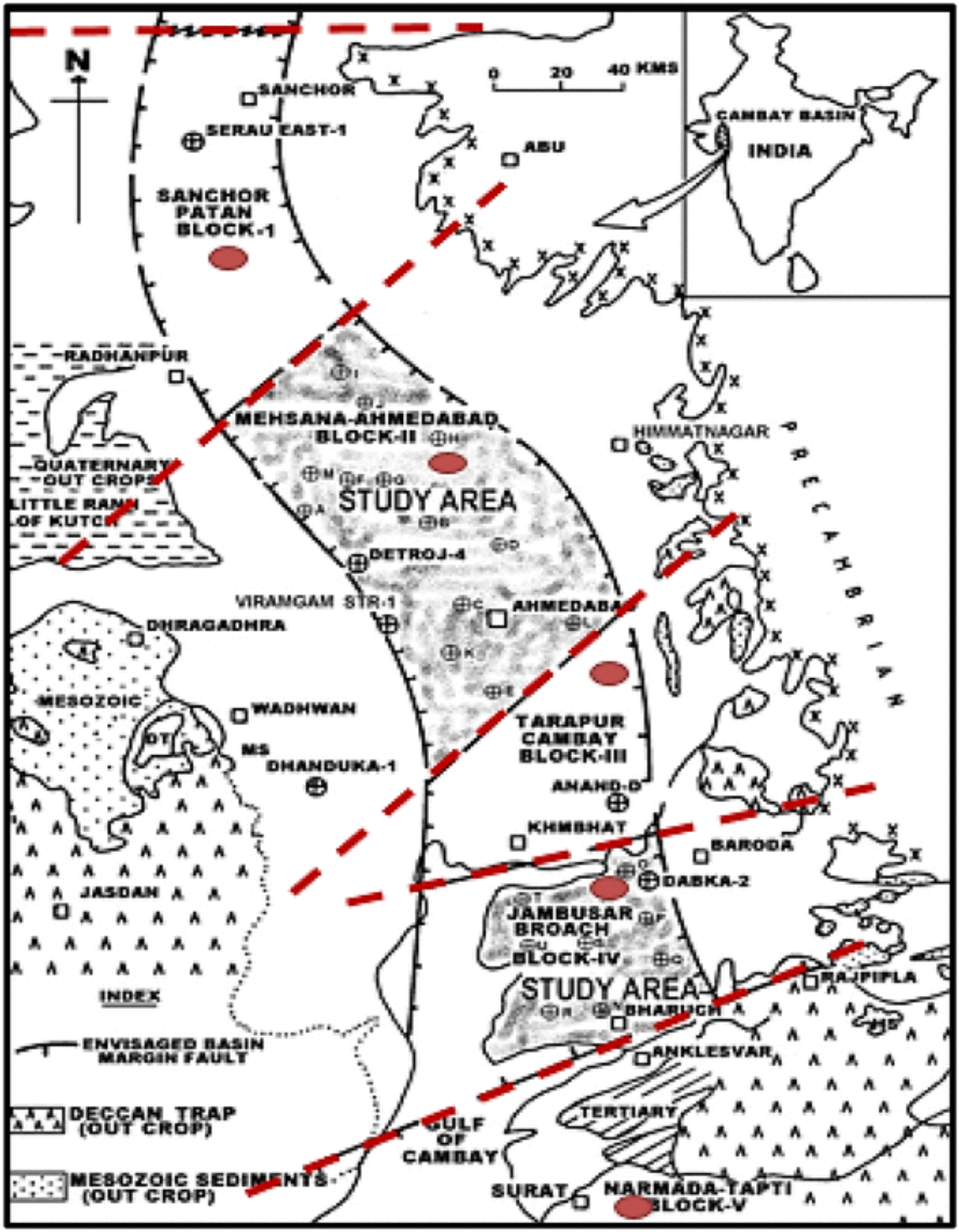

Figure 2 represents 5 tectonic blocks of Cambay basin, Western part, India. (Biswas, 1977)

4. STUDY AREA

Sanand field (Figure3) which is our study area is situated in Ahmedabad -Mehsana block

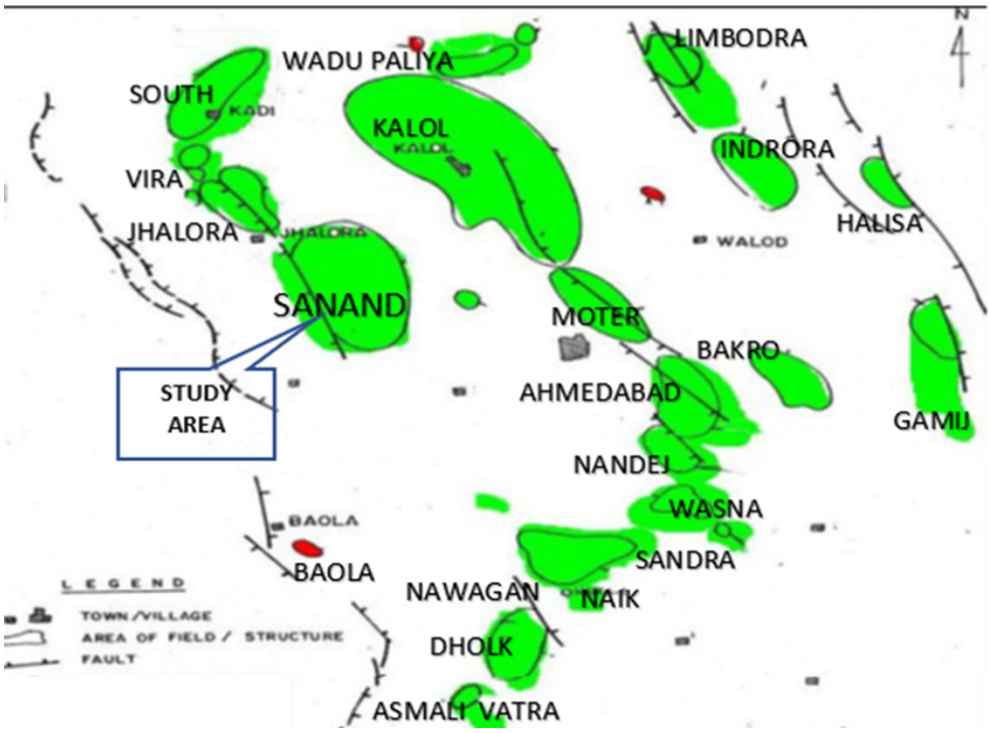

Figure 3 shows the Location map of different oil fields of Ahmedabad block and study area of Sanand field (Chandra, 1965)

Sanand field is located 25 Km of North – West of Ahmedabad (Figure 3). It is characterized by a geological structure of an elongated doubly plunging anticline trending NNW – SSE. It is famous for hydrocarbon reservoir in Kalol, Cambay shale and Olpad formations. Kalol formation is productive with K – III being the primary producer in the Northern part and K – IV in the South (Saraf, et al., 2008). Sanand field is situated on a prominent anticline which is fold in rock layers where the dips downward on both sides of the structure, creating a potential trap for hydrocarbon. Kalol formation is known for its sandstone, shale, carbonaceous shale and coal lithologies.

Tectonic – Setting

The Sanand field is part of the Mehsana – Ahmedabad tectonic block, specifically on the South Kadi – Jharora – Sanand high trend within the Cambay basin.

Source of Hydrocarbon

The older Cambay shale is considered the primary source rock for the hydrocarbon found in the Sanand field.

Trapping Mechanisms

Hydrocarbon are entrapped within the Kalol formation by structural features (like the anticline) and stratigraphic variations, such as the coal seems acting as seals for migrating hydrocarbons (Sharma et al., 2019).

We will discuss the log data acquisition of K-III pay zone of well X of Sanand field as well as ELAN processed data of K-III pay zone to find out water saturation, effective porosity, volume of shalyness etc. As the ELAN software is dealt with Archie's equation, Indonesian equation and effective porosity, therefore, those equations are to be discussed as follows.

5. EQUATIONS OF WATER SATURATION OF THE RESERVOIR & DISCUSSION ABOUT EFFECTIVE POROSITY.

$$S_W^n = \frac{aR_w}{\phi^m \times R_t} \quad (1)$$

Where, S_w = Water saturation, n = Saturation index, a = Archie's constant, R_w = Resistivity of formation water ϕ = Porosity, m = Cementation factor, R_t = Resistivity of formation

The above equation is Archie's water saturation equation in clean formation. Clean formation means volume of shalyness in the reservoir should be less than 5%. In this case equation (1) holds good. But if the shalyness is greater than 5%, then Archie's equation is not applicable for finding water saturation of the reservoir. Due to presence of shalyness in the reservoir, the effective porosity of the reservoir is reduced. Effective porosity of the reservoir depends upon how the volume of shale is scattered in the reservoir. The presence of shale in the reservoir is as follows.

1. Laminated shale –it is taking certain volume of the reservoir as shown in figure 4 which reduces the total pore volume of the reservoir as a result effective porosity of the reservoir is reduced as shown in figure 4.
2. Dispersed shale – when the fine grain shale particles are dispersed within the reservoir, it occupies the space of the pore volume due to which pore volume of reservoir is reduced. Therefore, effective porosity of the reservoir is also reduced as shown in figure 4.
3. Structural shale – Here the shale particles are removing the sand grains and occupy the space of matrix grain of sand as shown in the figure 4. This shale particles are not occupying the pore space of the reservoir. Total matrix volume is same as before as a result the porosity of the reservoir is not disturbed and it is the same as before (figure 4).

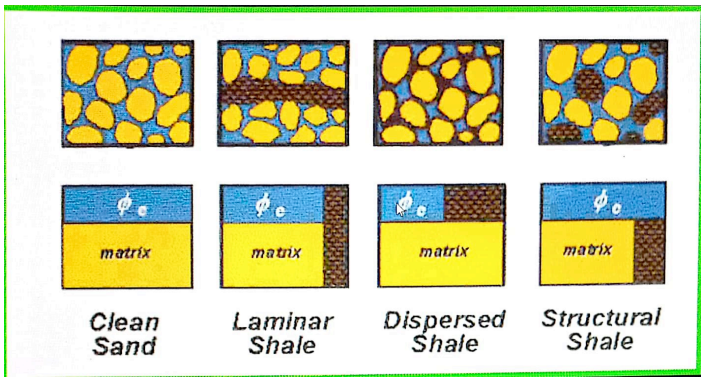

Figure 4 shows the effect of porosity due to presence of different type of shale in the reservoir. (Crain's Petrophysical handbook)

Due to presence of volume of shalyness in the reservoir as discussed above, the formation resistivity (R_t) can be written as follows.

$$\frac{1}{R_t} = \frac{V_{SH}}{R_{SH}} + \frac{1-V_{SH}}{R_{Sand}} \quad (2)$$

Where, R_{SH} = Resistivity of the shale., R_{Sand} = Resistivity of sand, V_{SH} = Volume of shale
Poupon-Leveaux has given the equation for finding the water saturation in shaly-sand reservoir as follows.

$$S_W^n = \left\{ \left[\left(\frac{V_{SH}^{2-V_{SH}}}{R_{SH}} \right)^{\frac{1}{2}} + \left(\frac{\phi_e^m}{a \times R_w} \right)^{\frac{1}{2}} \right]^2 \times R_t \right\}^{-1} \quad (3)$$

Equation (3) is known as Indonesian Equation as this equation is applied first in shaly-sand reservoir of the oil field of Indonesia and its validity is justified. Later this equation is universally accepted for any oil field of shaly-sand reservoir.

6. DATA ACQUISITION AND ELAN PROCESSED DATA INTERPRETATION OF WELL X, SANAND FIELD, CAMBAY BASIN, INDIA

Triple combo logging tools stack (High Resolution Induction Tool- Compensated Density- Compensated Neutron and Gamma Ray) has been lowered in a **well X** of Sanand field in Ahmedabad, Cambay Basin, India. The log motif is shown in figure 5. The first three track from the left side is the data acquisition and the last three tracks represent the processed data of petrophysical interpretation by ELAN software (Electro Log Analysis).

6.1. Data acquisition of Well X

The first 3 tracks from left side of figure 5 are described as follows.
The first track consists of Gamma ray, Caliper and SP log. The second track is the resistivity curves of high resolution deep (HDRS) and medium (HMRS) induction, DFL (Digital Focus Log) and true Resistivity of formation obtained from 'High Resolution Induction tool'. Third track is showing bulk density (RHOB) and neutron- porosity (NPHI) curves. From the first three tracks, it indicates that the interval from 1390 and below is the shaly formation where GR curve reads an average of 75 API, RHOB and NPHI curves are having huge separation between themselves and resistivity curves HDRS & HMRS also read resistivity value in the order of 1 to 2-ohm meter. Therefore, the interval 1390 to 1405 meters is considered to be shale.

K-III (Kalol- III) reservoir of well X of Sanand field
The interval 1384.7 - 1389.5 meters is considered to be K-lll (Kalol III) reservoir. In this interval GR curve reads nearly 30 API, RHOB and NPHI curves in this interval are very close to each other. Resistivity curves HDRS & HMRS within the interval from 1384.7 - 1386.2m are showing very high resistivity of value 23-ohm meter. This interval 1384.7 – 1386.2 m = 1.5m is considered to be oil bearing. The interval from 1386.2 – 1389.5 meters is water bearing as resistivity curves reads the resistivity value of 2-ohm meter only which is of low value of resistivity.

Well X – Sanand Field (Ahmedabad – Mehsana block of Cambay Basin)

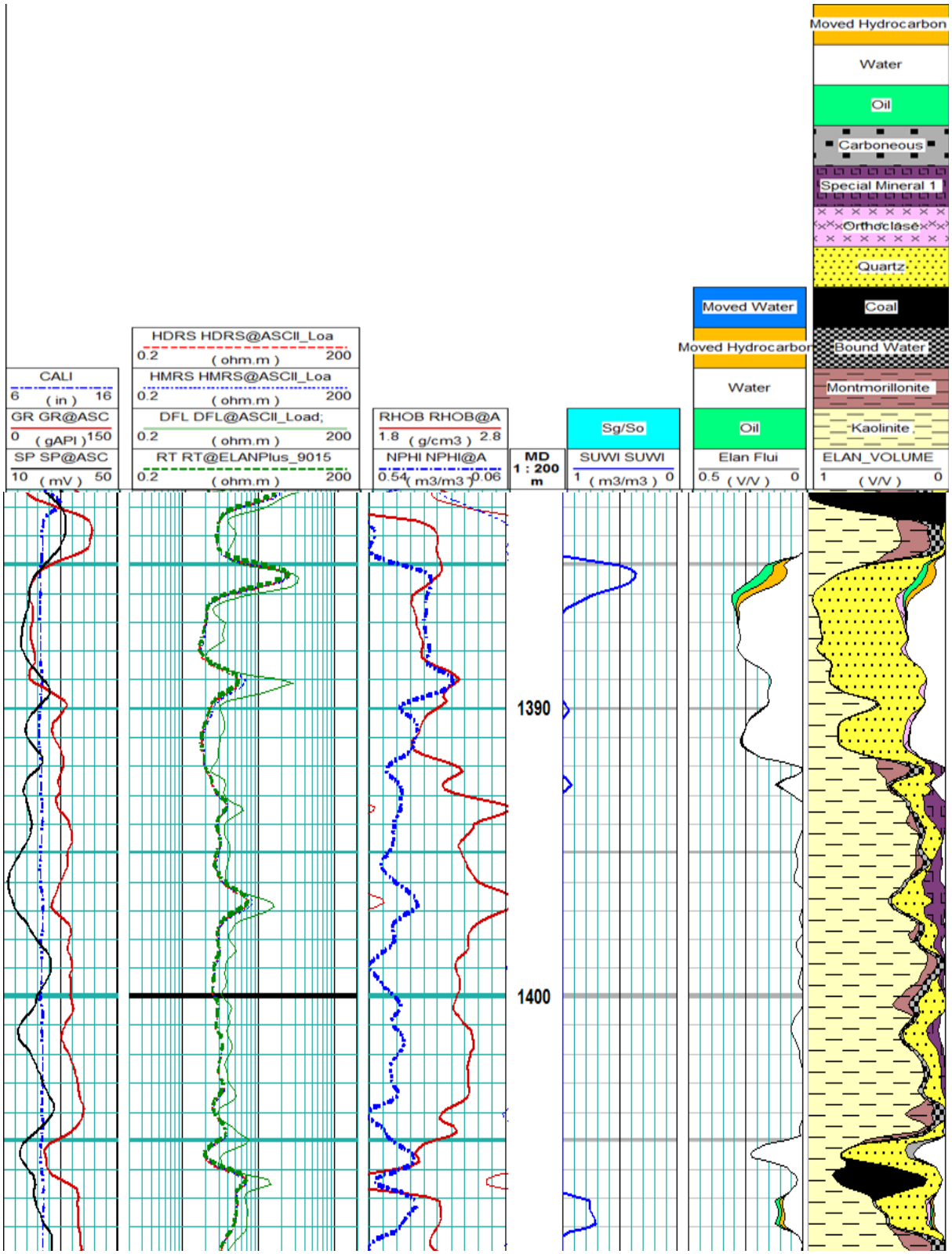

Figure 5 shows the data acquisition (first 3 tracks from the left) and ELAN processed data (last 3 tracks) of Well X, Sanand field. (Courtesy of Oil & Natural Gas Corporation Ltd., India 2013)

6.2. ELAN processed data of Well X

All the above data which are acquired from triple combo logging tools are stored as an input to the ELAN software for processing. The output of the ELAN is processed data as shown in figure 5 from fourth track to sixth track. Fourth to sixth track are ELAN processed data for finding water saturation, presence of minerals and rock types in the interval. Before processing the data, we monitored samples of cuttings data of drilling from which minerals choice is considered to put it as an input for processing. Here we have taken the mineral Kaolinite and Montmorillonite which are present in shale and Quartz minerals in sand obtained from cutting data. We also calculated moved hydrocarbon.

The fourth track is showing water saturation in the interval 1384.7 – 1386.2m is 37%. Therefore, oil saturation in this interval is showing 63% which is economically beneficial within this interval of 1.5m. The fifth track is showing 27% porosity in the interval 1384.7 – 1386.2m. Moved hydrocarbon is also shown in the fifth track.

The last track (6th track) is the summary of reservoir which is showing fluid and matrix part as a whole. The matrix part of the reservoir in the interval 1384.7 – 1392m is containing quartz (sand) and Kaolinite in shale. The pore volume contains fluids of water and oil.

As oil saturation is 63% in the interval 1384.7- 1386.2=1.5 m, the interval was considered to perforate for oil production. Production of oil of 50 Cubic meter per day was established from K-III formation, Sandstone reservoir of single porosity system.

7. CASE HISTORY OF FORMATION EVALUATION OF ONE WELL OF INDONESIA.

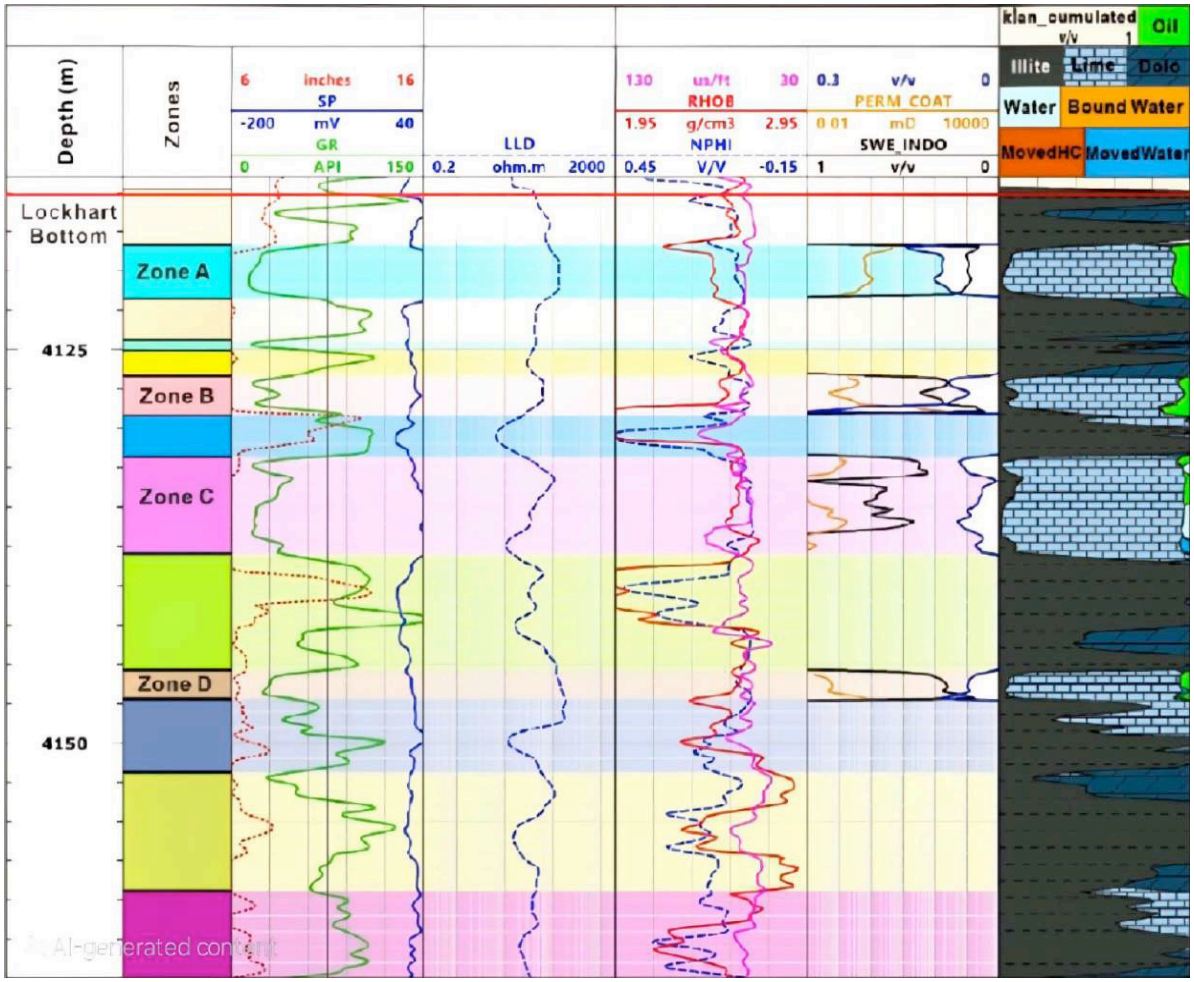

Figure 6 is the log data and ELAN processed data of one well of Indonesia. (by courtesy of Chevron Pacific Indonesia)

Figure 6 consists of 7 tracks out of which first 5 tracks from left are data acquisition tracks and last 2 tracks sixth and seventh are ELAN processed data. The first track is depth track, second track is zoning track, third track consist of Gamma ray, SP and calliper curves, fourth consists of LLD curve, fifth track consists of density and neutron porosity curves. Sixth track consists of effective porosity and water saturation curves and seventh track consists of matrix volume and fluid volume.

The figure 6 above is the log data and ELAN processed data within the depth interval 4120 – 4165m. There are four (4) zones, such as Zone A, Zone B, Zone C and Zone D. These four zones are limestone reservoir and is discussed about petrophysical analysis as follows.

Zone A

Zone A as shown in the figure 6 is a limestone reservoir.

Log data acquisition of Zone A:

$GR_{average}$ = average gamma ray = 15 API, SP = Spontaneous Potential is positive because of synthetic mud is used to avoid stuck up of logging tools.

LLD (Deep Latero Resistivity) > 100 Ω m, Φ_N = Neutron Porosity = 24%, Φ_D = Density Porosity = 30% , DT = Sonic Transit time = 62µs/ft

ELAN processed data of Zone A: (Indonesian equation for water saturation is used)

Φ_e = effective porosity = 10%, **S_w = water saturation = 16.66%, S_o = oil saturation = 83.33%**

K = coats permeability = 1md

Zone B

Zone B as shown in figure 6 is another limestone reservoir.

Log data acquisition of Zone B:

$GR_{average}$ = average gamma ray = 15 API, SP = Spontaneous Potential is Positive because of synthetic mud is used to avoid stuck up of logging tools.

LLD (Deep Latero Resistivity) = 80 Ω m, Φ_N = Neutron Porosity = 18%, Φ_D = Density Porosity = 24%, DT = Sonic Transit time = 62µs/ft

ELAN processed data of Zone B:

Φ_e = effective porosity = 7.5%, **S_w = water saturation = 33.3%, S_o = oil saturation = 66.7%**

K = coats permeability = 0.1md

Zone C

Zone C as shown in figure 6 is also a limestone reservoir.

Log data acquisition of Zone C:

$GR_{average}$ = average gamma ray = 20 API, SP = Spontaneous Potential is Positive because of synthetic mud is used to avoid stuck up of logging tools.

LLD (Deep Latero Resistivity) = 100 Ω m, Φ_N = Neutron Porosity = 18%, Φ_D = Density Porosity = 20%, DT = Sonic Transit time = 60µs/ft

ELAN processed data of Zone C:

Φ_e = effective porosity = 5%, Zone C top **S_w = water saturation = 41.66%,** Zone C bottom **S_w = water saturation = 66.66%**, Zone C top **S_o = oil saturation = 58.34%,** Zone C bottom **S_o = oil saturation = 33.34%,**

K = coats permeability = 0.1md

Zone D

Zone D as shown in figure 6 is also a limestone reservoir.

Log data acquisition of Zone D:

$GR_{average}$ = average gamma ray = 30 API, SP = Spontaneous Potential is Positive because of synthetic mud is used to avoid stuck up of logging tools.

LLD (Deep Latero Resistivity) > 100 Ω m, Φ_N = Neutron Porosity = 18%, Φ_D = Density Porosity = 20% , DT = Sonic Transit time = 60µs/ft

ELAN processed data of Zone D:

Φ_e = effective porosity = 5%, S_w = water saturation = 33.33%, S_o = oil saturation = 66.66%

K = coats permeability = 0.1md

From the above discussion of log data and ELAN processed data of one well of Indonesia, the effective porosity in four limestone reservoirs is of the order of 5 – 10 % only. Coats permeability is in the order of 0.1 – 1md considering very poor permeability. Density, neutron and sonic is giving the porosity which is primary porosity of limestone. The conventional tool in general cannot identify the secondary porosity of the reservoir. From the core data of the four zones it is observed in the core laboratory that the secondary porosity in limestone is of the order of 3% and total permeability is of the order of 450 md (core data not provided).

Primary porosities in these four-limestone zones are having less contribution of fluid flow from the reservoir. Most of the contribution of the oil flow is due to secondary porosity (3% porosity) which is having very high order of permeability of 450 md approximately. One zone data of zone C is contributing 2000 barrels/day. The above four limestone reservoir are having multi porosity system combination of primary and secondary porosity. The secondary porosity includes moldic, channel, fracture and vuggs as shown in figure 7.

These secondary porosities in limestone are responsible for increasing permeability to nearly 450 md in limestone reservoir as a result flow rate of crude oil of the limestone reservoir increased to many thousand barrels per day.

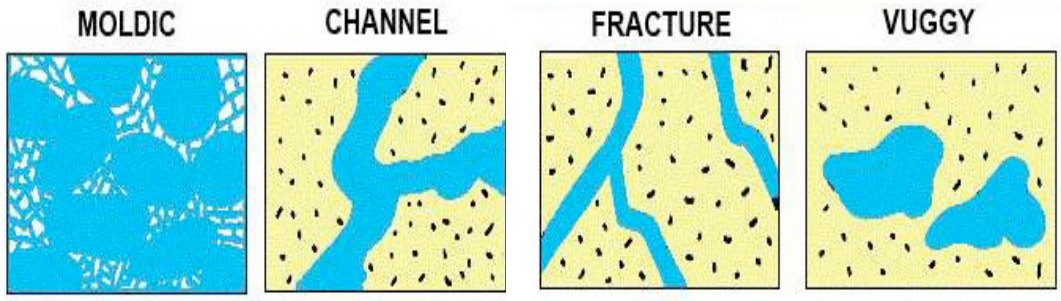

Figure 7 showing the secondary porosity in carbonate reservoir. (Crain's Petrophysical handbook)

8. DISCUSSION & CONCLUSION

1. K -III (Kalol formation) of Sanand field is sandstone reservoir which is single porosity system of primary porosity only. Primary porosity in the reservoir is also called the depositional porosity as it is formed at the time of deposition of the rocks. Grain sorting and packing of granules are responsible for primary porosity. Sandstone is the best example of single porosity system (primary porosity).

2. Multi porosity system is a combination of primary porosity and secondary porosity. Carbonate (limestone & dolomite) is the best example of multi porosity system. Secondary porosity is due to dissolution, dolomitization and fracturing.

3. Secondary porosity in carbonate is of the order of 2-5% only. But permeability in the carbonate reservoir is very high order due to the presence of secondary porosity. Most of the carbonate rock of different geological basins show many thousand barrels of production of hydrocarbon per day is due to secondary porosity and high permeability.

4. Well X of Sanand field is having sandstone reservoir which is single porosity system of primary porosity only. The effective porosity of this sandstone reservoir is 27%. No presence of secondary porosity in sandstone reservoir. Production rate per day from this reservoir is the order of 50 cubic meter or 315

barrels per day. Porosity is higher order but still now the production per day is less than 1000 BOPD. The production rate is less due to less permeability of the reservoir of the order of 20md (20md data of this reservoir of well X is obtained from build up pressure after shut in the well X by the reservoir engineer).

5. Reservoir zone C in the case history of one Indonesian well is a limestone reservoir having effective primary porosity of 5% only and Coat permeability is 0.1md. This reservoir of zone C is producing crude oil only of the order of 2000 BOPD. How this huge production from this reservoir is possible though the permeability is 0.1md? The answer is given from core data.

6. Core of zone C is collected and tested in core laboratory in details. Core data gives the value of secondary porosity is of the order of 3% only and permeability is of the order of 450md. This high permeability of the limestone of zone C is due to presence of 3% secondary porosity. Due to presence of secondary porosity and high permeability, the production rate of zone C has been reached up to 2000 BOPD.

7. From the above discussion, it may be concluded that multi porosity system of limestone reservoir is responsible to increase the high permeability of the carbonate reservoir although the secondary porosity is very less. This high permeability increases the productivity of the reservoir.

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Identification of Economic Benefits of Taro Cultivation for Small Scale Farmer Communities in Papua New Gunia, a Study based on Markham District in Morobe Province

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Abstract: The taro plays a vital role in contributing to rural economic growth and development in Papua New Guinea (PNG); however, the subsistence nature of its farming practices has hindered improvements in productivity and non-usage of modern agricultural practices, and emerging new technologies, which led to the unsustainable low-volume of supply which restricts access to export markets. In this context, this research aims to evaluate the challenges in taro cultivation and marketing practices. This study employs quantitative and qualitative methodological approaches, collecting data through 50 local taro farmers in Markam village in Morobe Province and interviews with key stakeholders in the taro value chain. The primary methods for analyzing this data are multiple regression, ANOVA analysis and focus group discussions. The findings indicate that taro farming has raised the income levels of rural households, thereby enhancing food security within the community and leading to improved nutritional, economic, and social stability in these areas. The main themes identified are the impact of climate change, the non-availability of agricultural inputs, and the non-existence of economic success factors. Furthermore, taro production is limited by several other challenges, including restricted market access, high transportation costs, and fluctuating prices in urban markets. Moreover, insufficient government extension service support throughout the supply chain is the main barrier to advancing this critical crop to the next higher level. The policy recommendations include further promoting the cooperative model for both cultivation and marketing, employing new marketing strategies through cooperative societies to improve market access, developing rural road infrastructure, addressing issues related to the climate changes on production, government intervention through the provision of reliable extension and training services, awareness programs on modern technology and updated cultivation methods for farmers, as well as offering additional financial and marketing assistance to strengthen this nationally important symbolic food crop in PNG.

Keywords: Agriculture, Taro production, Market Access, Rural Development, and Papua New Gunia; PNG.

1. INTRODUCTION

Taro (Colocasia esculenta) is a very ancient food crop and a staple food crop of immense cultural and nutritional significance in PNG. Historical records shows that this may be one of the oldest foods grown with irrigated system and was utilized in the highlands as early as 9000 years ago. It was the most important food crop in PNG until about 300 years ago when it was displaced in the highlands (above 1200m altitude) by the recently introduced sweet potato. In the lowlands, it remained an important food crop until the early 1940s (Bourke, 2012). Since then, taro production has been greatly reduced by a combination of taro blight, taro beetle and declining soil fertility. However, it is still the most important staple food crop in a limited number of remote inland locations including Markham. This plant is a perennial aquatic and cultivated as annually in swamps, lowland or up land fields. Taro has long been used as a staple food in the subsistence diet of PNG. However, expansion of urban centers and a growing market for new types of foods – like the diversity provided by taro – have transformed it from sustenance to more than just commercial potential. Taro is an

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important crop for the country, providing 6% of total calories for rural people (PNGNSO, 2010; Schmidt, 2024). Other studies based on FAO consumption data claiming an even higher percentage than this 6% (Mark, 2024).

It is also the ninth leading crop in terms of cultivated land area and the third in cultivated area among non-perennials (FAO,2004). This study carried-out a village in the Markham district of Morobe Province to ascertain the impact of taro production and marketing for rural development in that area. All farmers in this village are the members of a cooperative society of taro farming called the Markham Food Cooperative Society. The village's proximity to Lae provides a strategic advantage for transporting taro to the urban market. By examining the economic activities of Mamaringan villagers, it is possible to gain insights into the broader economic impact of taro production and marketing in the region. In overall, promoting food crop like taro in rural localities, country's standard cost of basic needs poverty line of 43% and 64% of healthy diet poverty line can be reduced (Mahrt, 2025).

2. RESEARCH QUESTIONS AND OBJECTIVES

Research Questions

I. What are the current production and productivity problems encountered by the taro farmers in Mamaringan village?
II. What are the main economic benefits of taro production to Mamaringan village in terms of rural development?
III. What are the challenges faced by taro farmers of Mamaringan in accessing to the Lae market?
IV. What are the main policies and strategies can recommend to improve the economic viability of taro production in Mamaringan village?

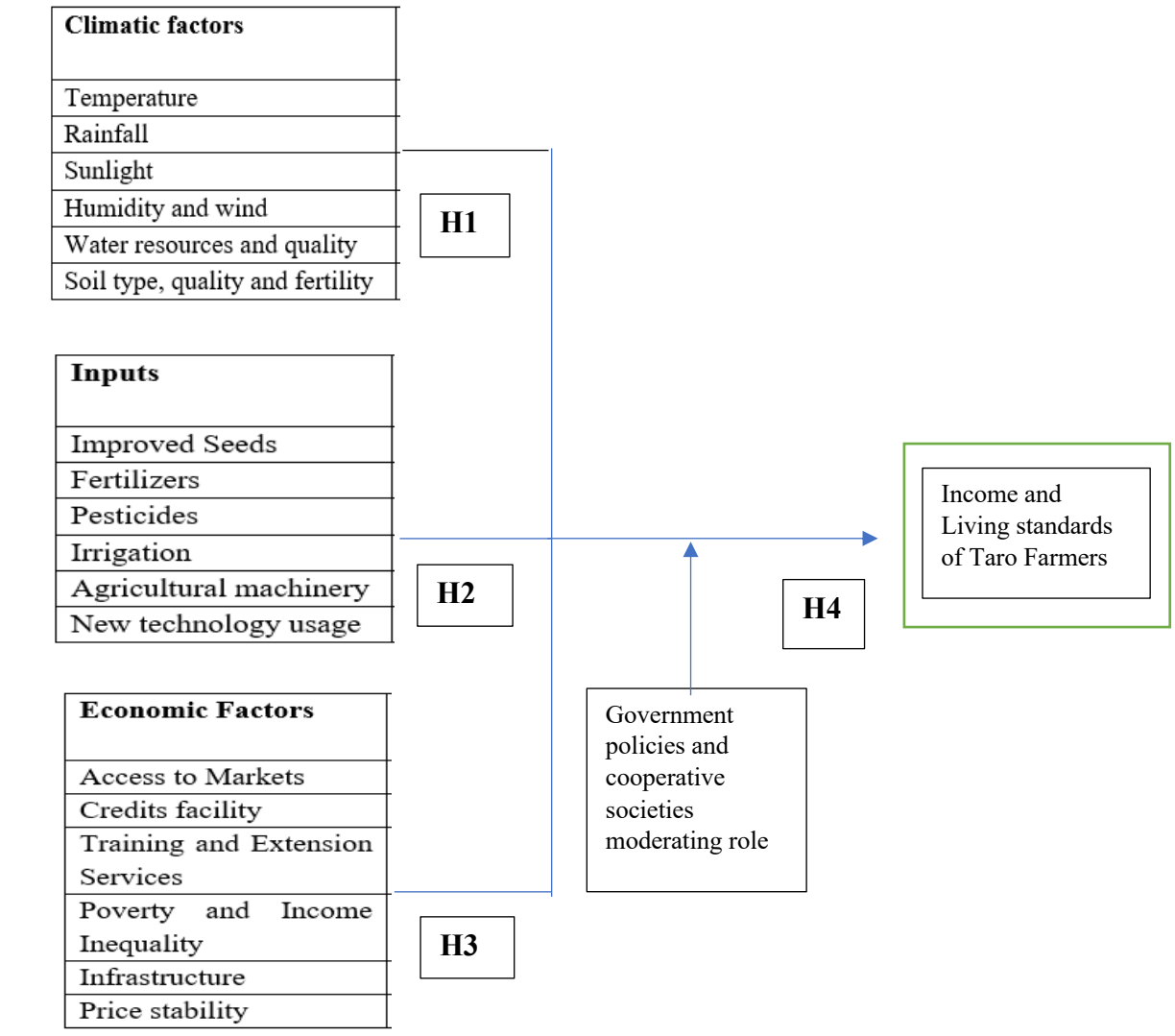
Research Objectives

I. Identify the main economic benefits of taro production to Mamaringan village in terms of rural development.
II. Investigate the challenges faced by taro producers in Mamaringan village in their overall supply chain including to access the surround markets.
III. Recommend policies and strategies to improve the economic viability of taro production in Mamaringan village.

3. METHODOLOGY AND CONCEPTUAL FRAMEWORK

This research designed to use mix methods with first quantitative and later qualitative approaches in view of developing a comprehensive case study. This case study aims to see social, economic or cultural aspects of taro production and marketing in the village through rural development perspective. The use of this mixed methods approach enhances the validity and reliability of findings through triangulation. The quantitative data will largely be used to measure key variables (such as taro sales, income, production levels and market prices), while the qualitative data will investigate community perceptions, experiences and social dynamics to generate some themes. In addition to the 50 interviews by using a structure questionnaire, several other faces to face interviews and group discussions carried-out with other stake holders and apex bodies in overall taro value chain. The conceptual framework outlines the key independent, dependent and moderating variables.

Conceptual Framework of the Study



Based on the above conceptual framework, the following four hypotheses have derived.

- H1: Non-addressing the climate changing factors have created negative impact for the taro production, quality and productivity in Mamaringan Village.
- H2: Non-availability of agricultural inputs has created negative impact for the taro production, quality and productivity in Mamaringan Village.
- H3: Non-availability of critical economic success factors has created negative impact for the taro production, quality and productivity in Mamaringan Village.
- H4: The government and cooperative societies have moderating role in improving income and living standards of taro farming communities in Mamaringan Village.

4. DATA COLLECTION AND ANALYSIS

Semi-structured interviews were conducted with key stakeholders, including taro farmers, local market vendors, cooperative members, and community leaders in Mamaringan Village. The interviews explore topics such as farming practices, challenges in production, market access, income levels, and the social and cultural significance of taro. This method allows for flexibility in probing deeper into certain issues while maintaining a consistent structure across interviews. These discussions were accompanied by groups of taro farmers to capture collective experiences and common challenges. Focus Group Discussions (FGD) are especially suitable for understanding community dynamics and opened discussions on topics that may not have come up in individual interviews.

Primary data collected from 50 farmer families in Mamaringan Village and 37 farmers are subsistence farmers and 10 are semi-subsistence and other 03 are small scale commercial taro growers. Gender wise 30% farmers are female and 20 farmers are males. Prices wise, they said they get good prices from supermarket chain in LAE city but difficulty to approach them because they need quality posh products possibly packeted ones. Second level prices they get from Lae main market and Mutzing market close to village give very low prices. A portion of households supplement their income by working wage jobs or non-farm businesses, in addition to selling cash crops and their own output. Nonetheless, 37 households in the 50 sample only participate in own-farm agriculture, making subsistence farming one of the distinguishing features of rural household livelihoods in this village. Please see the appendix for the field photos in interviews and focus groups methods in Mamaringan Village. Table 1 shows farmers perceptions on climatic factors affecting for the production of Taro.

Table. 1 – Farmers perceptions on climatic factors affecting for the production of Taro

Climatic Changing Factors	**No of responded families**	**Rank**	**%**
Temperature	40	2	80%
Rainfall	45	1	90%
Sunlight	10	4	20%
Humidity and wind	25	3	50%
Water resources and quality	45	1	90%
Soil type, quality and fertility	25	3	50%

Source: Structured questionnaire interviews

As shown in Table 1, farmers explain that climatic factors such as rainfall, water resources and quality, temperature, humidity and wind, soil type, soil quality and fertility, availability of water supply and its quality and sun light are badly affected for the volume and quality of the taro production. The percentages are shown their actual knowledge about these factors. The multiple regression model and the related ANOVA test carried out to check the validity of H1 hypothesis. Estimated regression results such as R Square (0.767), R Bar Square (0.698) and t and F statistics are significant and low value of SSE shows that non-address of climate change factors have negative impact for taro production. Therefore, the H1 hypothesis can be accepted with somewhat shaky scale data set. Now government and agricultural Apex and R&D bodies duty is the address these climate change factors successfully and help various level taro producers to stay in market competitively to push this industry to next higher level. However, the real impact of climate change on taro productivity and production must be carried-out via climatic econometric models such as DSSAT, IPSL-CM-1-6. The effects of climate change on agricultural output in PNG have not been extensively modeled previously, making the analysis of its impact on a crucial crop like taro vital for national food security. However final outcome of these on-going models-based studies is recommendation of government heavy investment in boosting productivity by creating improved taro varieties that thrive better in wetter and dry conditions, as well as enhancing the availability of fertilizers and other extension services via cooperative societies to farming communities. Table 2 shows farmers perceptions on impact of agricultural input availability for the production of Taro.

Table. 2 – Farmers perceptions on impact of agricultural input availability and knowledge about them for the production of Taro

Inputs	No of responded families	Rank	%
Improved Seeds	15	2	30%
Fertilizers	10	1	20%
Pesticides	10	3	20%
Irrigation	05	4	10%
Agricultural machinery	02	5	0.04%
New technology usage	01	6	0.02%

Source: Structured questionnaire interviews

As shown in Table 2, farmers explain the impact of agricultural input availability for the production of Taro. As shown in the Table 2, farmers knowledge on the new technology usage and agricultural machinery are very low may be due such information and awareness mechanism may not exist. Even other inputs such as irrigation, pesticides, improved seeds and fertilizers may also have such low values may be due to non-availability and unaffordability of them. The multiple regression model and the related ANOVA test carried out to check the validity of H2 hypothesis. Estimated regression results such as R Square (0.653), R Bar Square (0.618) and t and F statistics are significant and low value of SSE shows that non-address of agricultural input availability have negative impact for taro production. Therefore, the H2 hypothesis can be accepted with somewhat shaky data set. Now government and agricultural Apex and R&D bodies duty is the address of these agricultural input non-availability issues successfully and help various level of taro producers to stay in market competitively to push this industry to next higher level.

Table. 3 – Farmers perceptions on impact of economic factors for the production of Taro

Economic Factors	No of responded families	Rank	%
Access to Markets	45	2	90%
Credits facility	48	1	96%
Training and Extension Services	40	3	80%
Poverty and Income Inequality	40	3	80%
Infrastructure	45	2	90%
Price stability	35	4	70%
Availability of government supports in time	45	2	90%
Availability of cooperative society's supports in time	40	3	80%

Source: Structured questionnaire interviews

As shown in Table 3, farmers explain the severe impact of non-availability of credits facilities, non-accessibility to markets, poor infrastructure for the production of Taro. Lack of training and proper extension services from government, non-availability of marketing and business development supports from any sides, volatility of prices and poverty as other reasons for poor performance in this crop. The multiple regression model and the related ANOVA test carried out to check the validity of H3 hypothesis. Estimated regression results such as R Square (0.569), R Bar Square (0.545) and t and F statistics are significant and low value of SSE shows that non-address of critical economic factors have negative impact for taro production. Therefore, the H3 hypothesis can be accepted with somewhat shaky data set. Now government and agricultural Apex and R&D bodies duty is the address of these agricultural input non-availability issues successfully and help various level of taro producers to stay in market competitively to push this industry to next higher level. The impact of moderating factors such as availability of government supports in time and availability of cooperative society's supports in time did not check separately as a separate hypothesis (H4) because it covers in H3. However, these Likert scale data are

somewhat shaky. Therefore, it is better to carry out a Structural Equation Model (CB-SEM or PLS-SEM) to get understand real relationships between all these multiple variables by checking H4 in next stage of this research.

Focus group discussion with farming communities revealed that major constraints to taro production include diseases like Taro Leaf Blight (TLB), pests as taro beetle, poor soil management practices and declining fertility, lack of value addition to production and lack of efficient marketing systems. Some farmers said TLB and taro beetle are of prime importance since the former can reduce yield by up to 50 percent and can also lead to poor quality of the corms while the later can cause up to 95% crop loss due to damaged corms. Many groups appreciated the taro varieties developed by National Agricultural Research Institute (NARI) now widely adopted in this village as a result of mass scale distribution of material and awareness/promotion campaign, and already there are indications of the positive impact achieved towards food security and income generation for rural farmers. Further, the most farmers said they were satisfied and impressed with the performance of the three improved varieties (NT 01, NT 02 and NT 03) with their tolerance to TLB disease and higher corm yield per plant in comparison to the local varieties. However, for the locals in Mamaringan, they farm their own local varieties which are unique in taste including Lae yellow, Lae green and namkowi which is their original local unique variety. Numerous participants stated that their earning potential is shaped by the kind of crops they grow and the sales they make. Particularly, taro growers who grow cocoa and coffee make a lot of money because of a quick spike in market prices, which raises their level of living.

The taro farmers from Mamaringan used “slash-and-burn agriculture” to clear areas for subsistence agriculture. This method, which has been used by the indigenous population for a good number of years, involves burning small areas of forest to clear land for gardens, using the nutrients in the ash to help nurture plant growth. After the garden soil has lost much of its nutrients due to cultivation, farmers move to a new area, leaving the previous garden to revert to a secondary forest. While this tradition has been historically sustainable, there are concerns that PNG’s growing population, which has doubled in the last thirty years, may increase the effects of slash-and-burn agriculture on the most biodiverse forests. Those were what frequently mentioned by the local people of Mamaringan village about how they cultivate the land for taro farming as it is their stable food especially the area under study. Taro is one of the well-known food crops in Morobe and at this time now it is of high value than other food crops sold at the open markets within the province. Focus group discussion further revealed that in addition to its economic importance, taro has a long history of social and cultural attachment in PNG societies. In PNG, taro is a prized commodity for traditional social activities such as compensation payments, bride price ceremonies and feasts. Its importance stems from the crop’s unique taste. Possibly customary land tenure system also may be one of the impediments for growth of large-scale taro cultivation in this area as few tribal leaders explained in interviews.

Further, most of participants appreciated the efforts are underway to address challenges like declining soil fertility and water management to ensure sustainable taro production, introduction of new taro varieties resistant to blight and adaptable to different agro-ecological zones, and necessity of popularizing consumption of taro over the sweet potatoes in highland areas and among the new generation in PNG. Many group participants emphasized importance of small-scale short-term projects to improve the productivity and sustainability of taro production while popularizing local consumption and commercial exports. Participants in this group discussion explained that over the years rain fall as increased but temperature has not increased that much in these localities. This group discussion further revealed that some farmers cultivate new varieties of taro to tackle this temperature and rain fall issues but they said they tried alternative crops and farming techniques to minimize losses due to climate changes and reduce income losses with their timing actions. But overall effect of climate change in decreasing productivity they alone can not tackle. Therefore, government and related agricultural apex bodies badly need to addressed this issue in holistic manner. Access to and cost of a healthy food may be the biggest obstacle to achieving household welfare goals for a sizable portion of rural people in this village. Many participants said that funding rural feeder roads that reduce rural remoteness may have major welfare benefits to these taro cultivating communities in this province.

5. FINDINGS AND POLICY RECOMMENDATIONS

This study was mainly based on interviews through structured questionnaires, focus group discussions and selected stakeholder interviews to raise a few important themes for further research. Farmers' perceptions of climatic factors affecting the production of taro explain that climatic factors such as rainfall, water resources and quality, temperature, humidity and wind, soil type, soil quality and fertility, availability of water supply and its quality and sunlight are badly affected by the volume and quality of the taro production. The multiple regression model and the related ANOVA test were carried out to check the validity of the H1 hypothesis, and it proved that non-addressing the climate-changing factors have created a negative impact on the taro production, quality and productivity in Mamaringan Village. Therefore, in policy and strategy setting to minimize climate change's effect on agriculture is a timing requirement government and related Apex bodies pay attention to assisting poor taro farming communities (Thomas, 2025).

Taro farmers' knowledge of new technology usage and agricultural machinery is very low. It may be due to such information and awareness mechanisms may not exist in this village and surrounding localities. Even other inputs such as irrigation, pesticides, improved seeds and fertilizers may also have such low awareness values in Table. 2 may be due to the non-availability and unaffordability of them. The multiple regression model and the related ANOVA test were carried out to check the validity of the H2 hypothesis, and it proved that the non-availability of agricultural inputs has created a negative impact on the taro production, quality and productivity in Mamaringan Village. The application of fertilizers, pesticides, and herbicides and the use of improved seeds are not yet common across the households in this village for any crops they cultivated. This fact is further confirmed by the IFPRD researchers in 2023 with 14 provinces covered Household Survey in PNG (Schmidt,2024). Therefore, policies and strategies should set to make available agricultural inputs and dissemination of knowledge and awareness about importance of it, is another timing requirement for government and related Apex bodies act on.

Taro farmers in Mamaringan Village explained the severe impact of the non-existence of critical economic factors such as non-availability of credit facilities, non-accessibility to markets, poor infrastructure for the production of Taro. Furthermore, lack of training and proper extension services from the government, non-availability of marketing and business development supports from all sides, volatility of prices and poverty as other reasons for the poor performance of this crop. The multiple regression model and the related ANOVA test were carried out to check the validity of the H3 hypothesis, and it proved that non-address or non-provision of critical economic factors have a negative impact on taro production, productivity and marketing and export activities.

In Brisbane, Australia alone, there is a demand for three to four container loads per month, yet PNG can only supply one container due to many bottle necks in supply side. There are significant opportunities to export taro to regional markets like New Zealand, Australia and other Pacific countries, where many expatriates from PNG live. For instance, the National Agriculture Research Institute (NARI) in Lae celebrated the launch of its first shipment of 13 tons of premium Morobe taro to New Zealand on March 3, 2024 (Luma, 2024). Consequently, it is crucial for the government and relevant Apex organizations to create policies and strategies that address key economic factors impacting taro production and marketing, helping impoverished taro farming communities elevate their industry and quality of life. Additionally, in light of the upcoming food security challenges associated with rising population growth, advancing the taro sector is essential. Innovative initiatives like the TaroGen project are necessary to propel the taro industry to a higher level (Abner, 2009).

This project produced high yielding TLB resistant taro varieties in short period is no doubt an exceptional achievement for any conventional breeding program in PNG which gives farmers access to new TLB resistant taro cultivars (Yalu, 2009). However, the impact of climate change on taro productivity via econometric models (Hoogenboom, 2019; Jones, 2003; Jones, 2024) in PNG has not been carried-out by the researchers therefore, it is the national duty to promote this type of high-end econometric models-based research in understanding the climate change impact on important crop like taro to keep the national food security in-line. Available some studies (Smith, 2025; Thomas, 2025) revealed that projected reduction in agricultural yields between 2005 and 2050 from climate change is likely to be around 6.4% based on the IPSL model. The findings from these articles highlight the necessity for policy measures to be specifically designed to address the unique circumstances in all PNG rather one specific province.

In areas deemed more vulnerable, such as remote and economically disadvantaged parts of this Province, there is an immediate need for a targeted safety net initiative that addresses risks to agricultural productivity while also providing agricultural extension services, along with health and nutrition assistance. The well-being of rural communities would significantly benefit from the development and maintenance of rural feeder roads and bridges that connect more isolated areas to secondary and tertiary market hubs within this province. Constructing community infrastructure, such as roads and bridges, as part of a program that supports subsistence agriculture could help families dealing with production shocks by stabilizing sustainable incomes. Additionally, it may improve overall welfare by enhancing connections between rural and semi-urban areas in this province. Notably, there is extensive evidence globally that social protection measures (whether cash or in-kind transfers) assist low-income households in escaping precarious and food-insecure situations; however, PNG has yet to invest in a formal social safety net program despite having passed 50 years of political independence. While PNG is recognized as one of the most diverse tribal societies, no research has been conducted to examine significant connections between violence and household consumption expenditure. Given the sensitive nature of household and community conflicts in PNG, more comprehensive research into the impacts of violence on various outcome indicators is critically needed. Furthermore, there is a lack of empirical data assessing whether rural households in Morobe Province that cultivate taro can sufficiently meet other essential needs while adhering to nutritional dietary guidelines. This concern was prominently voiced by numerous participants during our focus group discussions.

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APPENDIX

Fieldwork Photos

Photo. 1: Semi-structured interviews in Mamaringan carried out by Research Assistants led by Ms. Noel Naida

Photo. 2: Focused Group Discussions

Photo. 3: Field works - Participants' Observations

Photo.4: Drone View of the Markham Food Cooperative Taro Farm in Mamaringan Village

A Socio-economic Development of PNG AND Mozambique from 1975 to 2025: A Statistical Analysis

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Abstract: When we celebrate the Golden jubilee of our country's independence, it is significant to study Papua New Guinea (PNG) and Mozambique because both countries gained their political independence in 1975. This paper titled, a socio-economic development of Papua New Guinea and Mozambique from 1975 to 2025: A statistical Analysis, will use four sets of statistical data; (a) Gross national product, (GDP), (b) the national government expenditure (NGE), (c) the per capita of GDP, and (d) the per capita of GNE of two countries to analyse socio-economic development of Papua New Guinea and Mozambique in half a century. The research discovers that PNG had a higher level of the GDP and the NGE, than Mozambique in the 50 years of independence. It also discovers that PNG had a higher level of per capita GDP and per capita GNE in the same period. Th paper will facilitate the research and development of economics, economic-social development of Papua New Guinea.

Keywords: Papua New Guinea (PNG), Mozambique, socioeconomic development, economy, independence.

1. INTRODUCTION

This is a socio-economic Development of PNG AND Mozambique from 1975 to 2025: using statistical data of two countries. Papua New Guinea and Mozambique gained their political independence in 1975.
The purpose of the paper was to discover whether Papua New Guinea, or Mozambique had performed well with respect to four sets of statistical data; (a) Gross National Product, (GDP), (b) the National Government Expenditure (NGE), (c) the per capita of GDP, and (d) the per capita of GNE. The data analysis was done using the US$ for fifty (50) years, so that we may perceive and understand the long-term trends of the four set of statistical data, between 1975 and 2025. The main research questions are as follows;
What are the *average annual population growth rates of* Papua New Guinea and Mozambique?
What are the *average annual gross domestic product and the national government expenditure growth rates of* Papua New Guinea and Mozambique?

The research discovers that PNG had a higher level of the Gross National Product (GDP) and the National Government Expenditures (NGE), than Mozambique in the 50 years of independence. It also discovers that Papua New Guinea had a higher level of per capita GDP and per capita GNE in the same period. This research also identified some negative impacts, (1). There was a rapid growth of population in the 50 years period; and (2) Also there was a rapid growth in bribery or corruption in the country that could influence the long-term developments of Papua New Guinea in the coming years to come.

The reminder of this paper is organized as follows: Section 2 analyses the growth of PNG's gross domestic product (GDP) and national government expenditure (NGE) from 1975 to 2025. Section 3 discusses the growth of Mozambique's GDP and NGE of 50 Years. Section 4 examines the GDP per capita and the NGE per capita of PNG from 1975 to 2025. Section 5 explores a Generative Pre-trained Transformer (GPT) and presents GPT survey. Section 6 looks at challenges encountered in PNG and will face its future. The final section ends this paper with a few concluding remarks and suggestions for future work.

A Socio-economic Development of PNG AND Mozambique from 1975 to 2025: A Statistical Analysis
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Table 1 A Comparative study of **(GDP), (NGE),** the per capita **GDP** and the per capita **GNE** of **PNG** and **MOZAMBIQUE, 1975-2025**

Year	Est Total Population of Papua New Guinea	Est Total Real GDP of Papua New Guinea (in US$)	Est Total Real National Government Expenditure (US$)	Est Real Per Capita Expenditure (US$)	Est Real Per Capita GDP of PNG (US$)	Est Total Expenditure of PNG Mozambique	Est Total Real GDP (In US$)	Est Total Real Government of Mozambique Mozambique (In US$)	Est Real Per Capita GDP Expenditure of Mozambique
1975	2,774,000	6,180,000,000	429,310,000	2228	155	10,170,000	5,750,000,000	600,000,000	565
1976	2,852,000	5,900,000,000	455,160,000	2069	160	10,440,000	5,240,000,000	620,000,000	502
1977	2,933,000	6,020,000,000	457,490,000	2053	156	10,740,000	5,300,000,000	650,000,000	493
1978	3,015,000	6,540,000,000	426,710,000	2169	142	11,040,000	5,540,000,000	650,000,000	502
1979	3,098,000	6,660,000,000	498,380,000	2150	161	11,340,000	5,820,000,000	710,000,000	513
1980	3,183,000	6,501,000,000	521,780,000	2042	164	11,630,000	4,620,000,000	680,000,000	397
1981	3,270,000	6,490,000,000	675,190,000	1985	206	11,750,000	3,585,000,000	828,000,000	305
1982	3,359,000	6,510,000,000	633,850,000	1938	189	11,820,000	3,662,000,000	776,000,000	310
1983	3,449,000	6,720,000,000	696,940,000	1948	202	12,070,000	3,280,000,000	846,000,000	272
1984	3,540,000	6,700,000,000	593,480,000	1893	168	12,320,000	3,417,000,000	520,000,000	277
1985	3,632,000	6,960,000,000	569,030,000	1916	157	12,550,000	4,516,000,000	458,000,000	360
1986	3,725,000	7,290,000,000	608,500,000	1957	163	12,770,000	5,303,000,000	368,000,000	415
1987	3,820,000	7,490,000,000	704,590,000	1961	184	12,820,000	2,395,000,000	376,000,000	187
1988	3,916,000	7,710,000,000	764,500,000	1969	195	12,800,000	2,199,000,000	408,000,000	172
1989	4,013,000	7,600,000,000	867,370,000	1894	216	12,910,000	3,529,000,000	498,000,000	273
1990	4,111,000	7,370,000,000	799,540,000	1793	194	13,300,000	3,855,000,000	484,000,000	290
1991	4,210,000	8,080,000,000	899,690,000	1919	214	13,330,000	3,000,000,000	505,000,000	225
1992	4,310,000	9,200,000,000	1,041,360,000	2135	242	13,810,000	2,800,000,000	452,000,000	203
1993	4,411,000	10,870,000,000	1,225,780,000	2464	278	14,370,000	3,120,000,000	530,000,000	217
1994	4,513,000	11,520,000,000	1,023,940,000	2553	227	14,950,000	3,320,000,000	732,000,000	222
1995	4, 416,000	11,130,000,000	791,870,000	2520	179	15,480,000	3,390,000,000	380,000,000	219
1996	4,720,000	12,000,000,000	1,026,310,000	2542	217	15,960,000	3,770,000,000	444,000,000	236

1997	4,425,000	11,530,000,000	951,350,000	2606	215	6,400,000	4,200,000,000	597,000,000	656
1998	4,931,000	11,020,000,000	684,370,000	2235	139	16,810,000	4,620,000,000	770,000,000	275
1999	5,038,000	11,300,000,000	598,340,000	2243	119	17,000,000	5,160,000,000	770,000,000	304
2000	5,145,000	11,000,000,000	583,420,000	2138	113	17,710,000	5,220,000,000	890,000,000	295
2001	5,528, 435	11,000,000,000	500,260,000	1989	90	18,220,000	5,850,000,000	104,000,000	321
2002	5,924,003	11,000,000,000	460,040,000	1857	78	18,760,000	6,390,000,000	130,000,000	341
2003	6,123,997	11,000,000,000	549,510,000	1796	90	19,330,000	6,830,000,000	141,000,000	353
2004	6,238,041	11,530,000,000	601,420,000	1848	96	19,910,000	7,370,000,000	154,000,000	370
2005	6,353,905	12,260,000,000	1,512,500,000	1930	238	20,490,000	7,860,000,000	162,000,000	384
2006	6,747,720	12,920,000,000	1,600,000,000	1915	237	21,080,000	8,630,000,000	178,000,000	409
2007	6,963,345	13,930,000,000	1,720,200,000	2000	247	21,670,000	9,290,000,000	191,000,000	429
2008	7,183,002	13,890,000,000	2,310,000,000	1934	322	22,280,000	9,970,000,000	205,000,000	447
2009	7,406,438	14,890,000,000	2,864,400,000	2010	387	22,890,000	10,600,000,000	221,000,000	463
2010	7,633,523	16,430,000,000	2,621,300,000	2152	343	23,530,000	11,000,000,000	246,000,000	467
2011	7,859,346	16,520,000,000	6,465,900,000	2102	823	24,190,000	12,130,000,000	282,000,000	501
2012	8,081,390	17,930,000,000	6,758,000,000	2219	836	24,860,000	13,010,000,000	326,000,000	523
2013	8,302,698	17,950,000,000	7,255,100,000	2162	874	25,560,000	13,920,000,000	395,000,000	545
2014	8, 523,441	20,380,000,000	4,600,000,000	2391	539	26,260,000	14,950,000,000	467,000,000	569
2015	8,743,246	21,720,000,000	1,512,500,000	2484	173	27,040,000	15,950,000,000	506,000,000	590
2016	8,961,718	22,920,000,000	1,624,600,000	2558	181	27,700,000	16,560,000,000	609,000,000	598
2017	9,178,714	23,730,000,000	4,180,000,000	2585	455	28,600,000	17,180,000,000	629,000,000	601
2018	10,190,000	23,660,000,000	4,900,000,000	2322	481	29,440,000	17,770,000,000	592,000,000	604
2019	10,690,000	24,720,000,000	5,279,000,000	2312	494	30,300,000	18,180,000,000	613,000,000	600
2020	11,220,000	23,850,000,000	6,510,000,000	2126	580	31,300,000	17,960,000,000	495,000,000	574
2021	11,780,000	23,810,000,000	5,740,000,000	2021	487	32,300,000	18,390,000,000	3,000,000,000	569
2022	12,030,000	25,170,000,000	6,930,000,000	2092	576	33,000,000	19,470,000,000	3,210,000,000	590
2023	12,280,000	25,940,000,000	7,200,000,000	2112	586	34,300,000	20,520,000,000	3,600,000,000	598

2024	12,576,502	27,000,000,000	7,500,000,000	2147	611	35,300,000	21,300,000,000	518,000,000	603
2025	12,800,000	28,000,000,000	7,800,000,000	2188	609	36,300,000	22,360,000,000	610,000,000	616

Sources: The sources for PNG and Mozambique are drawn from historical records and estimates from United Nations and World Bank, GPT was accessed in June 2025. Largely, the populations were estimated from the national censuses and the international data sets for both countries. Also for both countries' population estimates soon after 1975 were largely based on projections and national demographic surveys. The financial statistical data for both countries in constant US$: Using the GPT the constant financial statistical data were estimated using the various national and international sources. The specific sources are identified as shown: The United Nations, the World bank, the International Monetary Fund (IMF), and the Index Mund.

2. THE GROWTH OF PNG'S DOMESTIC PRODUCT (GDP) AND NATIONAL GOVERNMENT EXPENDITURE (NGE) FROM 1975 TO 2025

Error! Reference source not found. reveals the detailed calculations of the gross domestic product (GDP), the National Government expenditures (NGE), the GDP per capita and the NGE per capita of the two named countries--Papua New Guinea and Mozambique.

What is the date of Sources for PNG and Mozambique? For Papua New Guinea, different sources were used: the United Nations, the World Bank, the Bank of Papua New Guinea, the PNG national censuses of the country and other data. Different sources were used for Mozambique: The United Nations; the World bank; the different population estimates based on original data and also the different projections after 1975.

From this section on, we will analyze the results in some detail below, in terms of;

1. Growth of PNG's Domestic Product (GDP) and NGE of 50 Years.
2. The Growth of Mozambique's GDP and NGE of 50 years.
3. The GDP per Capita and the NGE per Capita of PNG from 1975 to 2025.
4. The GDP per Capita and the NGE per Capita of Mozambique from 1975 to 2025.

2.1 Growth of PNG's Domestic Product (GDP) of 50 Years

In 1975, PNG's GDP was estimated to be US$6.18 Billion. In 2025, PNG's GDP had increased to be an estimated US$28 Billion. Overall, in the increase for 50 years, there was an increase of US$21.82 Billion, for PNG. There was a growth of about 353.07% in the 50 years. This represented an estimated growth of 7.06% GDP growth per year for each of the 50 years.

2.2 Growth of PNG's National Government Expenditure (NGE) OF 50 YEARS

In 1975, the NGE of PNG was estimated to be US$429 Billion. In 2025, the NGE of PNG was estimated to be US$7,800 Billion. Overall, there was a growth of US$7,371 Billion, in the 50 years. Thus, there was an estimated growth of 1,718.18% of the NGE in 50 years; which represents a growth of about 34.36% per year, for each of the 50 years.

3. THE GROWTH OF MOZAMBIQUE'S GDP AND NGE FROM 1975 TO 2025

3.1 The Growth of Mozambique's GDP of 50 Years.

In 1975, (the same years as when PNG gained her independence), the GDP of Mozambique, was estimated to be US$5.7 Billion GDP. In 2025, Mozambique's GDP growth was estimated to be about US$22.36 Billion. In 50 years, the Mozambique's GDP had increased to be about US$16.90 Billion. This implies that the growth in 50 years, was estimated to be 296.49%, overall, in Mozambique. For Mozambique, there was a growth rate of about 5.92% per year, in each of the 50 years. In contrast, for PNG, the annual GDP growth rate for each of the 50 years was about 7.06% per year. This implies that PNG had an annual growth of about 1.14% per year, above Mozambique.

3.2 The Growth of Mozambique's GDP and NGE of 50 Years

In 1975, Mozambique's NGE was estimated to be about US$ 6 Billion. In 2025, the NGE of Mozambique was estimated to be about US $6.10 Billion. Overall, Mozambique's NGE grew an estimated US$10 Million, in 50 years. This was a growth rate of about 166.66%, in the 50 years. For each of the 50 years, there was a GNE growth rate of an estimated 3.33% per year for Mozambique. By contrast, in PNG there was a growth of an estimated 34.36% per year for each of the 50 years; while a similar annual growth for Mozambique of her GNE was 3.33%.

4. THE GDP PER CAPITA AND THE NGE PER CAPITA OF PNG FROM 1975 TO 2025

4.1 Changes in PNG's GDP per Capita from 1975 to 2025

In 1975, the GDP per capita of PNG, was about US$2,228. In 2025, the GDP per capita had *declined* to US$2,128 per head of population in PNG. There was a *decline* in the GDP per capita of PNG, overall, by about US$100 per head, in 50 years. This information is important to PNG leaders. The information shows that in 50 years, there was a *decline* in the per capita GDP in PNG by about US$2.00, per head.

The information also, seems to imply that per capita income in PNG had been *declining* over time, without the PNG leaders and the general public noticing the gradual downward trends, in 50 years.

Of course, the declines over time, may been quite gradual! However, it seems that many PNG leaders and the majority of the PNG people may not have been aware of the gradual *declines*. There may have been a number of possible causes, which are identified.

First, a superficial implication is that there had been delays in increases of the minimum wages in PNG, over the years, for example, in 2025.

Second, the wages of the grassroots farmers in PNG may have been ignored without a genuine justification. Why should PNG government neglect or ignore the wages of the rural farmers? Why does PNG government only maintain the minimum wages of the urban or the city workers in PNG? After all, they are the citizens of PNG.

Third, there had been a general rising of the population of PNG over time, with no or little efforts taken by the government to slow them down, or to control them; through PNG's family planning, health measures, and other means. Why so? In the long-run, the ignorance or negligence may have important implications for the future! For example. Long-term poverty could increase in PNG.

But what are the implications for future of PNG? We will briefly discuss the two points regarding the implications for future of PNG.

First, population, income and welfare: One important reason as to why many Western countries, may have a generally higher per capita GDP, or a generally higher welfare, is that there are relatively smaller population levels, or a smaller population growth rates, than in the developing countries; such as Papua New Guinea.

Second**,** generally higher economic impacts: Also in many Western countries, generally, the lower are the population, or the lower are the growth rates; the higher are the GDP per capita, or the higher are the living standards, overall. Papua New Guinea needs to learn from the hints, given by the Western countries, in relations to impact of her population and per capita income; which had declined in the first 50 years of independence.

In light of the *declining per capita GDP*, a brief survey was conducted by the author, about PNG for the last 50 years.

5. A GENERATIVE PRETRAINED TRANSFORMER (GPT) SURVEY

Generative Pre-trained Transformer (GPT), is a state-of-the-art language model developed by OpenAI. GPT uses deep learning techniques to generate natural language text, such as articles, stories, or even conversations, that closely resemble human-written text. GPT was introduced in 2018 as part of a series of transformer-based language models developed by OpenAI (Source: Accessed on https://encord.com/glossary/gpt-definition/, August 26, 2025). This section uses the generative pretrained transformer to conduct a GPT survey**.**

We carried out a brief survey using the GPT. The author wanted to discover the average annual growth rates of seven (7) areas, in the developed countries (DC); and similar growth rates for the less developed countries (LDC) in the world.

QUESTION 1: What are the average annual population growth rates in the following seven (7) areas in the developed countries (DC)?

Regarding, the growth rates the GPT provided the following answers: Europe: 0.1%; USA: 0.20%; Canada: 1.28%; Japan: -0.5%; Australia:1.2%; New Zealand: 1.0% per year (Source: GPT accessed 06th July 2025).

QUESTION 2: What are the average annual population growth rates for all the less developed countries (LDC) in the world? The GPT provided the answers. The GPT showed that all the less developed countries (in 2025), have an approximate population growth rates estimated to be 1.2% to 2.5% per year (Source: GPT accessed 06th July 2025). Details of the results are available from the author.

6. CHANGES IN PNG'S NGE IN 1975-2025

In 1975, the NGE per head of population in PNG was US$155. In 2025, the NGE per head of population was US$609. Overall, for the 50 years, the NGE per capita in PNG had grown by US$454. The amount translates to an overall increase of an estimated 292.92%, overall, in 50 years. The level represents a growth of 5.86% per year, in each of the 50 years.

6.1 Growth of Population of PNG and Mozambique in 1975- 2025

In 1975, the population of PNG was estimated to be 2.8 million people. In 2025, the population of PNG was estimated to be 12.8 million people. In 50 years, the net level of PNG's population was 10 million, which was a growth of 357.14%. There was an estimated 7.14% growth per year in each one of the 50 years.

In 1975, the population of Mozambique was estimated to be 10.1 million people. In 2025, the population of Mozambique was estimated to be 36.3 million people. This was a growth of 26.2 million people; which was an estimated growth of 259. 41%. There was an estimated 5.19% growth for each one of the 50 years.

Thus, the average annual growth rate of PNG's population was estimated to be 7.14%; while those of Mozambique was 5.19%. Both have higher rates than that for most of the less developed countries!

7. THE GDP PER CAPITA AND THE NGE PER CAPITA OF MOZAMBIQUE FROM 1975 TO 2025

7.1 Growth of GDP per Capita in Mozambique in 1975-2025

In 1975, the estimated GDP per capita was about US$565. In 2025, the estimated per capita GDP in Mozambique had increased to US$616. The overall level of growth was estimated to be US$51, in 50 years. Overall, the amount translates to a growth of an estimated 1.2% per year, for each one of the 50 years. In contrast, there was a *decline* of about US$2.00 per head of the per capita GDP in PNG, in the 50 years.

7.2 Growth of NGE per Capita in Mozambique in 1975-2025

In 1975, the NGE per capita for Mozambique was an estimated US$59. In 2025, the estimated NGE per capita had d*eclined* to US$7. Overall, there was a *decline* of US$52, in the 50 years. Also, overall, the level of decline of the NGE per head was an estimated 113.46%, in the 50 years. But, for Mozambique the annual rate of *decline* of the NGE per head, for each of the 50 years was 2.27%.

8. CHALLENGES FACING PNG AND ITS FUTURE

From a bird's eye-view, the paper concludes that generally, whilst PNG may have had, higher trends in the results, of the four data sets, many other non-physical aspects, had created many negative impacts for Papua New Guinea. For Papua New Guinea, there had been, at least two important impacts about the long-term outcomes. First, unlike in many Developed Countries (DC), there had been a rapid growth of population in the 50 years period, as shown in Table 2

Table 2 Population of the Provinces in PNG

SUMMARY DATA ABOUT 20 PROVINCES															
PROVINCE/DATA, INFORMATION	TOTAL POPULATION	CITIZEN POPULATION	GROWTH RATE 1980-2000 (%)	TOTAL LIT RATE (%)	VOTERS (2007)	HEALTH CENTRES	POPN SERVED BY HEALTH CENTRES	NUMBER OF NURSES	POPN SERVED BY NURSES	MORT PER 1000 UNDER 5 YRS	TOTAL LIFE EXPECTANCY	FOOD CROPS: (%ENGAZED)	(% FOR CASH)	ELECTRICITY CUSTOMERS	% POPN WITHIN 5 KM NATIONAL RDS
CENTRAL	183983	29742	2.3	72.1	99827	29	6344	48	3883	62	56.4	7.3	13.7	3182	63
GULF	106898	17043	2.6	56.9	49474	23	4648	87	1229	160	46.4	73.7	11.7	411	24
MILNE BAY	210412	38942	2.5	78.1	92179	41	5132	181	1162	97	54.1	82.8	9.1	1340	21
NCDC	254158	35188	3.6	90.7	94451	14	18154	54	4707	27	59.2	14.4	5	41766	100
ORO	133065	21840	2.7	69.7	60400	19	7003	83	1603	81	54.5	73.3	7	961	50
WESTERN	153304	22564	3.3	71.3	59722	38	4034	157	976	92	54.3	65.5	5.8	652	17
EASTERN HIGHLANDS	432972	99483	2.2	43.9	355203	32	13530	70	6185	73	55.4	76.7	11.9	5445	45
ENGA	295031	50609	2.9	35	250424	28	10537	104	2837	97	52.5	79.7	9.3	1396	63
SIMBU	259703	54472	1.9	41.8	219385	31	9619	111	2341	73	56.8	81.2	7.9	1721	72
SOUTHERN HIGHLANDS	546265	94069	4.2	36.5	390720	56	9755	259	2109	84	55.2	78	6.8	1131	65
WESTERN HIGHLANDS	440025	95693	2.5	38.4	415291	32	13751	233	1889	63	56.2	77.7	13.2	6175	73
EAST SEPIK	343181	65231	2.2	52.7	174215	37	9275	176	1950	115	52.2	75.7	9.7	2380	44
MADANG	365106	60709	2.7	55.2	157371	38	9608	196	1864	113	51.1	76.3	13.3	3297	36
MOROBE	539404	95774	2.8	63.6	227441	39	13831	310	1740	118	51.7	69.2	12.5	12136	34
SANDAUN	185741	31589	2.4	44.4	91316	31	5991	83	2238	163	46	75.4	9.1	1070	34
AROB	175160	30932	1.5	76.7	54839	32	5474	130	1347	74	59.6	76.7	14.3	570	41
EAST NEW BRITAIN	220133	39220	2.5	81.6	76307	29	7591	244	904	73	57.1	74.4	25.7	6496	61
MANUS	43387	7942	2.6	85.8	21313	12	12.4	53	819	59	58.6	68.1	12.4	3353	36
NEW IRELAND	118350	22053	2.9	77.4	48072	30	3945	109	1086	69	57.9	75.2	55.1	1202	5
WEST NEW BRITAIN	184508	30672	3.6	70.7	70037	27	6834	153	1206	74	56.7	69.5	14.1	1982	60
TOTAL/AVERAGE	**5190786**	**943767**	**3**	**62**	**150399**	**31**	**165068**	**2841**	**42075**	**88**	**55**	**69**	**13**	**96666**	**47**

Source: National Research Institute, Papua New Guinea District and Provincial Profiles, National Research Institute, March 2010

Second, there had been a rapid growth in bribery or corruption in the country. As a result, one perceives that in the next 50 years, PNG may see some negative changes. It was perceived that the problems may have been caused by the rising bribery or corruption, not being successfully decreased or controlled in Papua New Guinea, see Figure 1.

Figure 1. An Index of Bribery and Corruption in PNG

The Island of Bougainville may become independent country soon, separating from the mainland of PNG. This outcome may cause other provinces, to create similar problems. (At the date of the paper, Bougainville has not seceded from Papua New Guinea, yet). However, it is believed that this particular outcome, could create a possible disintegration of a once, peaceful, and a blessed country.

9. CONCLUSION

The purpose of the paper was to provide a review of the gross national product (GDP), the national government expenditure (NGE), the per capita of GDP, and the per capita of GNE of two countries, PNG and Mozambique, both had gained political independence, at the same year, in 1975. In summary, PNG and Mozambique had increased the GDP and the NGE over time, between 1975 and 2025. However, regarding the per capita GDP and the per capita NGE, there were declines, which are summarized.

For PNG, there was a *decline* in the GDP per capita in PNG, overall, by about US$100 per head for the 50 years. The information implies that in 50 years, there was a *decline* in the per capita GDP in PNG, by about US$2.00, per head. For Mozambique, there was a *decline* of US$52 in the 50 years. Also overall, the level of decline of the NGE per head was 113.46%, in the 50 years. However, the annual rate of *decline* of the NGE per head, for each of the 50 years was 2.27%. In future work, we will delve into the inequality distributions and populations in provinces of PNG.

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All errors of facts or judgments belong to the author.

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Assessment of Markham Bridge Concrete Deck's Health by Schmidt Hammer Test

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Abstract: This paper strives to assess the current health condition of the concrete of the bridge deck of Markham bridge of Papua New Guinea (PNG). The existing quality of concrete is tested through non-destructive testing (NDT) method. Schmidt hammer is used to assess the health condition. Vertical values were used for calculation of the in-situ compressive strength of concrete at 24 locations spanning along the entire length and breadth of the bridge deck. The compressive strengths at various locations related to the surface hardness based on empirical and statistical approach were calculated. The current quality of concrete in most of the locations is typically fair, not good. At one location, the compressive strength is calculated to be 18 MPa which is not acceptable for reinforced concrete construction and indicates need of immediate attention of the authority for pre-emptive measures to protect the bridge from further deterioration and untoward event in future. The School of Civil Engineering may be engaged with the Department of Works and Highways (DOWH) of PNG for more rigorous studies on the rehabilitation or replacement issues with the cost escalation for this purpose.

Keywords: Non-destructive test, Markham bridge, current health, concrete bridge deck, Schmidt hammer.

1. INTRODUCTION

Existing health condition of the concrete of the bridge deck of Markham bridge of Papua New Guinea (PNG) is assessed through non-destructive testing method. It is the longest bridge in Papua New Guinea and across the largest river in PNG. It connects mines with Lae, the largest sea port in the country (PNG). The steel-concrete composite bridge spans across the Markham River and is situated on the Wau-Bulolo highway which connects Bulolo to Lae, the second largest city and the largest sea port of Papua New Guinea. The road is the only medium of communication for over 200000 people who lives in the adjacent area and depend on it for communication with Lae. It is an important road for transportation of local raw and extracted materials like wood, gold or coffee and that of industrial products like furniture also. The length of the bridge is 560 m. It is the longest bridge of PNG and was worst affected by flood in 2004. The approach road on Lae side was washed out by 2004-flood. Pier no. 3 was subsided due to scouring caused by flood water. Japanese organization came into action after subsiding of pier no. 3 to reinforce pier no. 1 to 4 to protect the bridge from complete failure. In 2006, repair of approach road and bank protection was done by AusAID. The objective of the project by Japanese organization was to revive essential functions for some decades with repair and strengthening of piers and abutments.

The project was completed successfully but Japan International Corporation Agency (JICA) team mentioned for substantial measures for better operation of the highway. Different agencies worked on this Bridge ranging from British, Australian to the Japanese agencies across the largest river Markham in PNG. Different study groups addressed the river system and effects of flood on the infrastructure and especially on bridges in PNG. Gibson et al. studied on bridge failures in Papua New Guinea induced by floods (Gibson & Matsumoto, 2019). Study on the social impact of highway construction on Markham valley has been conducted by N.T. Ha (2022). Implication of dynamic geodic datum has been studied (Stanaway, 2004). El-

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nino and climatic risk assessment as well as mitigation measures for PNG has been reported (Bang et al., 2002). Governance issues in the construction of bridges and roads have been published by another study group (Hughes, 2000). Benefits of rehabilitation of roads in six provinces of PNG has been studied and reported (Jusi et al., 2007).

Role of other nations on the sustainability issue of PNG is addressed (Huettmann, 2023). The erosion and drainage problems in Lae has been studied and reported (Atkins, 2013). JICA published a short communication on the urgent rehabilitation of Markham bridge after disastrous flood damage in 2004. A comprehensive report on proposed design of Markham bridge was published by Takaue (2010). Estimation of flood vulnerability zone with geo-spatial technology has been studied by Morea and Samanta (2020). Issues related to mining in Morobe Province, and a major tributary of Markham River in PNG has been addressed (Roche & Mudd, 2014). But a study on the existing health condition of the concrete in the bridge deck slabs of Markham bridge is yet to be noticed and that is addressed in this paper.

2. MATERIALS AND METHODOLOGY

The existing hardened concrete is tested by non-destructive technique with the help of Schmidt Hammer. The original version of the Schmidt hammer used for the investigation is shown in Fig. 1.

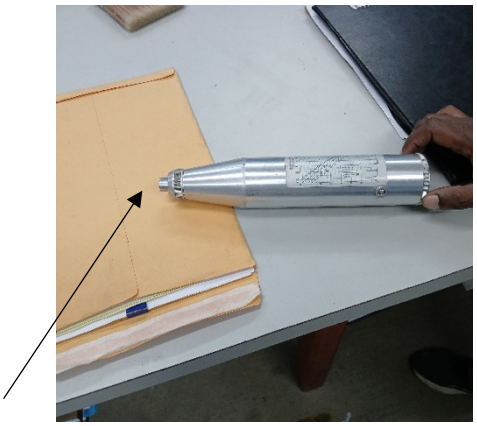

Fig. 1 Schmidt Hammer

The plunger was placed perfectly vertical [Fig. 2] at each location. At each location, there was a grid of 15 rectangular boxes at centre of which the readings were recorded after hitting the concrete surface and rebounding of the hammer. The average value of the readings was calculated as per the procedure published in the booklet of the manufacturer. There were 24

Fig. 2 Vertical position of the plunger during hitting the concrete surface.

locations and at each of such locations, 15 readings from the rectangular grid were recorded. As such the total number of readings recorded were 15X24 = 360. The plunger was hit
against the concrete surface at each location and it was locked after each rebounce. The hammer values were recorded after stability with the help of the scale attached to the hammer. These are the rebound values of the hammer. In this way total 360 hammer values were recorded along the full 560 meters length of the bridge. These readings were based on the surface hardness of the concrete surface and the hammer values were recoded for further calculation and analysis of the readings.

3. LOCATION PLAN AND DATA OBTAINED FROM THE SITE

3.1 Location Plan

The length of the bridge was measured with the help of the wheel meter which was observed to be 560 m. The width of the bridge was measured with the steel tape and was found to be 6 metres. The entire surface of the bridge deck of 560 m length from expansion joints at the extreme edges of the bridge was divided into 24 locations. The centre to centre (C/C) distance of each division along length was 50 metres and that between the edge and the first line of measurement was 0.6 m from the breadthwise edges; while the C/C distance between the location along width was 4.8 meters as shown in Figure 3 on the next page.

3.2. NDT Data

The non-destructive testing data (Schmidt rebound values) from 360 points (from 15 boxes at each of the 24 locations) were recorded sample data of 5 such locations are presented in the tables for location 1 through 4 and location 24 on next page.

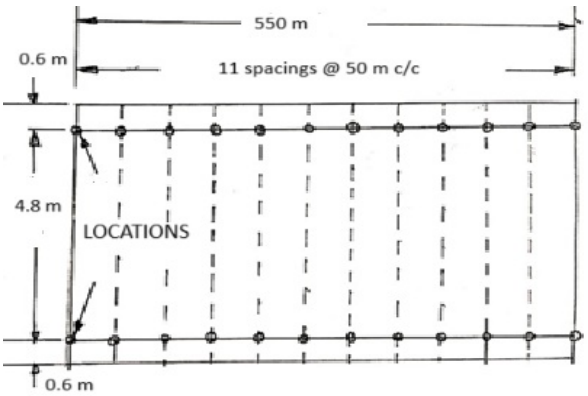

Fig. 3 Location of the test grids

NDT Data:

Locaton 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
27	18	32	22	26	25	45	32	26	38	27	29	26	44	22

Locaton 2

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
23	30	26	32	36	28	28	30	34	26	32	28	44	34	26

Locaton 3

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
26	20	28	20	26	32	26	28	32	38	26	24	26	38	24

Location 4

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
30	24	26	26	24	28	28	22	28	32	28	32	32	30	28

Locaton 24

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
24	25	27	28	25	22	27	25	21	25	29	24	26	24	22

3.3 Calculation of Average Schmidt Rebound Values

The sample calculation for the average Schmidt rebound value of the Schmidt hammer rebound values is furnished below:

1. Preliminary average =29
2. No of values other than 29 = 14
3. Upper limit = 29+14 = 43
4. lower limit = 29-14 = 15
5. No. of usable values = 13
6. Total of usable values = 439-44-45 = 350
7. Average value = 350/13 = 26.92 ~ 26

The average Schmidt rebound values for the first 12 locations and the next 12 locations are tabulated in Table 1 and Table 2 on the following page.

3.4 Compressive Strengths Calculation

The compressive strength from the average Schmidt hammer rebound values were. The compressive strength from the average Schmidt hammer rebound values were determined from the conversion graph provided by the manufacturer. The cube compressive strength values were calculated in MPa from the plot of the compressive strength versus hammer values.

Table 1 Average rebound values for first 12 locations

Location No	Ave. Rebound Values
1	26
2	29
3	27
4	28
5	27
6	26
7	26
8	27
9	23
10	27
11	27
12	25

Table 2 Average rebound values for the next 12 locations

Location No	Ave. Rebound Values
13	26
14	28
15	29
16	29
17	29
18	25
19	28
20	28
21	27
22	25
23	29
24	25

The compressive strengths are tabulated in Table 3 and Table number 4.

Table 3 compressive strengths of concrete for Average rebound values for first 12 locations		
Location No	Ave. Rebound Values	Comp. strength (Mpa)
1	26	22
2	29	26.5
3	27	24
4	28	25
5	27	24
6	26	26
7	26	26
8	27	27
9	23	18
10	27	24
11	27	24
12	25	21

Table 4 compressive strengths of concrete for Average rebound values for next 12 locations		
Location No	Ave. Rebound Values	Comp. strength (Mpa)
13	26	22
14	28	25
15	29	26.5
16	29	26.5
17	29	26.5
18	25	21
19	28	25
20	28	25
21	27	24
22	25	21
23	29	26.5
24	25	21

4. RESULTS AND DISCUSSION

It is to be noted that the Schmidt hammer rebound values are based on the surface hardness of the concrete surfaces. Schmidt correlated these rebound values to the existing compressive of the concrete himself also. Some correction for the values were also recommended. It is also to be observed from the aforementioned tables that the strengths at various locations were significantly low. As per the practices, the quality of concrete is poor if the average rebound number is below 20 and very good if the average value is above 40. The quality is regarded as fair if the average rebound number is between 20 to 30 and good if it is between 30 to 40. The quality of concrete at a number of locations are fair but not good or very good for the safety of the traffics. Moreover, the bridge is vibrating during passage of each heavy vehicle severely, which is also not acceptable from serviceability point of view. It can also be noted that none of average rebound number is below 20. Hence the quality is not poor but at location 9 it was 23 and the compressive strength corresponding to that value was calculated to be 18 MPa. As per Indian Standard also, the concrete grade for reinforced concrete should not be below M20 with characteristic compressive strength 20MPa. From that point of view, the quality of concrete at location 9 is not acceptable for reinforced concrete construction.

5. CONCLUSION

The existing quality of concrete is tested by Schmidt hammer. Vertical values were used for calculation of the in-situ compressive strength of concrete at 24 locations spanning along the entire length and breadth of the bridge deck. The compressive strengths at various locations related to the surface hardness based on empirical and statistical approach were calculated. A better approach may be a hybrid testing with Schmidt hammer and Ultrasonic pulse velocity through the concrete deck. The current quality of concrete in most of the locations is typically fair and not good. Moreover, the bridge was severely vibrated during passage of each heavy vehicle which not acceptable from serviceability point of view. At one location, the compressive strength is calculated to be 18 MPa. Even as per Indian standard the minimum grade of concrete needed for the reinforced concrete construction is M20 with the characteristic compressive strength of 20 N/mm^2 (20 MPa) which indicates, this concrete is not acceptable for reinforced concrete construction and indicting need of immediate attention of the authority for pre-emptive measures to protect the bridge from further deterioration and untoward event in future.

6. ACKNOWLEDGEMENT

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Impacts, Challenges and Opportunities of Cloud Computing in Department of Works and Highways

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Abstract: The concept of cloud computing has been around since 1960 when J. C. R Licklider observed that users can share multiple computer resources remotely at any one time. This idea became reality when Microsoft in 2008 introduced its first ever cloud platform Azure which enabled users to share and access information such as videos, music, links and files. The Papua New Guinea National Department of Works and Highways (DOWH) embraces this digital technology by adapting the cloud-based Asset Work Manager (AWM) system which stores and manages road data. The system houses analytical tools such as RAMS/BAMS, GIS and HDM4 where the road data collected on site including project reports is uploaded onto the cloud server and analyzed to produce reports and patterns to guide decision making in road investments. With the aid of the cloud platform, road network planning has improved significantly from planning and programming of capital and maintenance works to implementation, monitoring and reporting. Like any other digital technological inventions, the cloud technology has its own challenges from a product perspective as well as user perception such as lack of expertise within DOWH to manage it, data security concerns, inefficient internet accessibility to all 22 provincial establishments, budget constraints, environmental factors and workforce adaptation. These challenges can be solved through creative thinking, capacity development, collaboration with cloud service providers such as PNG DataCo, improve internet accessibility and open dialogue with all stakeholders. The use of cloud and other digital technologies is here to stay with further developments and advancements expected in the future, therefore the department remains receptive to the changes and will use the technologies to its advantage while at the same time managing the challenges.

Keywords: Asset Work Manager (AWM), Bridge Asset Management System (BAMS), Department of Works and Highways (DOWH), Highway Development Module (HDM4), Road Asset Management System (RAMS).

1. INTRODUCTION

The overall Papua New Guinea Road Network is a system of roads and bridges that connects the four regions (Highlands, Southern, Northern & New Guinea Islands) and twenty-two provinces of the country. The existing network has a total length of about 30,000km of which 8,830.30km are national roads and 22,000km are provincial and district roads or in other description referred to as sub-national roads. These roads carry the majority of the passenger and freight traffic in the country and are vital for social and economic development. The Papua New Guinea Department of Works and Highways (DOWH) is in charge of the national road network in ensuring its serviceability, safety and sustainability while the Provincial and District Governments take carriage of the sub-national roads. Each year subject to funding availability, the department engineers from the Asset Management Branch in collaboration with the provincial engineers from the DOWH provincial establishments undertake road data collection exercises where information such as road asset inventory, road condition (IRI), traffic volume, safety, climate vulnerability, bridge condition and others such

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as project reports are collected and uploaded onto the department's road management system called the Asset and Work Manager System (AWM).

This system is able to analyze the data using analytical software such as Highway Development Management Module 4 (HDM4) and produce results that are used to guide decision making in road development and maintenance investments. Over the years, the department has manually collected road data through the use of pen and paper till more recently laptops and gadgets like tablets have been used. These data are taken back to the office and analyzed which is a painstaking process to come up with the results. Storage of these information are usually kept in the on-premise servers or hard drives by individuals on excel files formats or printed hard copies. Main challenges and risks associated with this practice includes data security issues, time consumption, cost, manpower constraints and access to information in real time to influence decision making.

To address these issues and further improve road network planning, the Department of Works and Highways opted for the Asset and Work Manager System. The AWM system is cloud based, uses field-based applications for data collection, has GIS function to produce maps and ultimately serves as a one single source of truth system. As opposed to past scenario, access to information is real time as it is cloud based plus data is no longer required to be manually recorded as the field-based application allow data to be collected on site using tablets or android phones and uploaded instantly. The analytical function is also built into the AWM system, thus ensuring network planning decisions such as development of maintenance and capital budgets are evidenced based. The cloud technology has also enabled real time visibility of road asset inventory including information about the various road improvement and development activities on the network. Other software or applications can be seamlessly integrated or interfaced with the cloud-based road management system, thus increasing efficiency and resourcefulness. Importantly, standalone and outdated systems can be easily hacked, and manipulated by hackers who can steal valuable data from the inventory. With this cloud platform, there exist several layers of data security and safety, thus the road data is secured and reliable.

Road network planning in the Department will no longer be the same. With the introduction of cloud platform, we will monitor the performance of our roads and in the process develop long-term maintenance and capital works program to ensure optimal performance of the national road network whereby it stimulates socio-economic development.

Cloud computing is a technology that uses the internet to provide on-demand access to various IT resources, including servers, storage, and applications. It allows data and programs to be stored and accessed over the internet rather than on a local hard drive. This technology is beneficial because it reduces costs, provides easier access, decreases management expenses, and offers higher reliability. Examples of cloud services include Google Drive, Apple iCloud, Amazon Cloud Drive, Microsoft One Drive, and Oracle Cloud. Cloud computing is based on the concept of "Everything-as-a-Service" (XaaS), which includes Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS), and Infrastructure-as-a-Service (IaaS) (Soni, 2025). Cloud computing is changing the way people handle tech resources these days, no more waiting around for IT experts to set everything up. Instead, users jump straight in and grab the computing power they need, right when they need it. This self-serve model means companies can adjust their resources on the fly scaling up or down almost like turning a dial based on real time demand. Cloud storage has changed the way we handle data in ways that you might not expect. Organizations now lean on distributed, remote servers to hoard huge amounts of information, leaving behind the constraints of physical hardware often a game changer when data expands faster than ever. Companies can shift resources around much more nimbly, boosting their return on investment. Plus, the broad set of analytics and management tools offered by cloud providers gives businesses insights that weren't that easy to come by before (Seal, 2025).

An industry that is impacted by cloud technology is the road sector. Cloud technology plays an important role in terms planning through to actual construction and sustainability of the infrastructure. Road transportation infrastructure assets are not only expensive to construct but also costly to manage, to satisfactorily meet public anticipation. Management of road asset infrastructure facilities is challenging particularly in developing countries because of the low level of industrialisation. An industrial revolution provides reasonable ways of managing existing assets in a way that provides maximum benefit to the public taking into consideration limited financial resources (Estache, 2000). To store and manage road asset data, a Road Asset Management System (RAMS) is required. A Road Asset Management System is a strategic and systematic process of maintaining, upgrading, and operating road assets effectively. Asset management uses information to look at the whole road network rather than individual schemes. It is about collecting physical inventory and managing current conditions based on

strategic goals and sound investments (Patil, 2019). Road data such as road inventory, pavement, structures, traffic, road safety to name a few are critical data input that are normally uploaded, stored and managed in the AWM which is then able to guide decision making in terms of road investments by providing network information, assist with road development planning, develop works programming and overall manage the life cycle of the roads.

In the "Pavement Maintenance Management System: A Review", (Sarsam, 2016) of the University of Baghdad explains the two types of road maintenance management system, the first being the information system, which collects, organizes and stores data as network information and the second type which is the decision-support systems, which comprises applications modules to process the data and provide the information on which decisions can be based, and ultimately, implemented. For these systems to work effectively and efficiently, there must be a database where road data such as condition data, traffic data, safety and others are stored. In the Department of Works and Highways, the Asset and Work Manager is ultimately the road management system that stores and manages road data. This system is hosted with on premise severs which are managed by our ITC team. Over the years, it has become increasingly costly to sustain the ITC infrastructure coupled with manpower constraints, skills gaps, data security concern, poor internet accessibility, absence of road planning software and difficulty to access the data seamlessly. It is for these reasons that DOWH has opted to develop a road management system that is cloud based. By adapting cloud computing, we anticipate delivery of computing resources, such as servers, storage, and software, over the internet, rather than storing or processing them on local devices. This will allow our users to access these resources on demand, as needed, without needing to manage the physical infrastructure. Figure 1 below illustrates the Pavement Maintenance and Management system framework which articulates multiple road data streams which can be managed efficiently with cloud system.

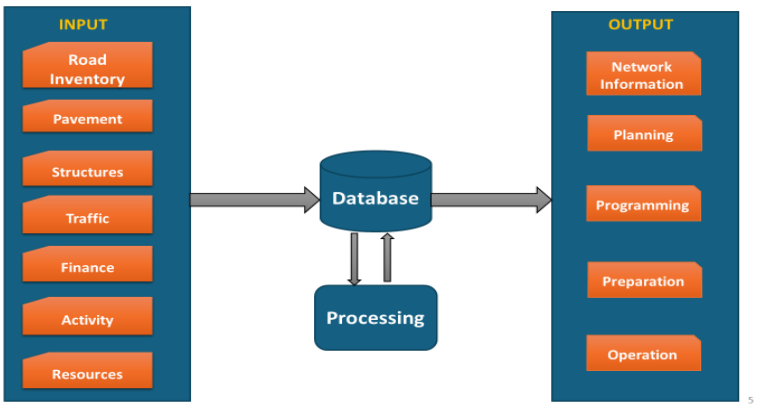

Figure 1. Basics and Concepts of Pavement Maintenance Management System (Sarsam, 2016). Modified by Solomon Pela (2025)

A cloud-based inventory and asset management system will empower the Department of Works and Highways to track and monitor its road assets, inventory status, and logistics in real-time, and get accurate business insights to make smart business decisions. Traditionally, the department performed this task manually, with pen and paper, or spreadsheets which has proven to be time consuming, costly and most times the data vulnerable to security threats such as manipulation of data. Ultimately, the road data must be analyzed to guide decision making in road investments and with the introduction of cloud computing, this is made possible and efficient. Cloud-based asset and inventory management systems can also have data analytics software, and data monitoring tools, which combined with real-time insights can give unprecedented control and transparency over the operations. Analytics can be effectively used to find the trends, and the insights related to demand and supply, and this translates to powerful business intelligence for optimizing all aspects of your operations (Sinha, 2022).

The objectives of this case study are to discuss the impact of cloud computing in the Department of Works and Highways in terms of road asset management, its challenges and opportunities. The study will also

give an overview of the Department's current road management system and the thinking behind adapting a cloud-based system compared to the previous system which relied on servers kept on premise as well as the National Government's position on cloud computing in PNG.

2. CLOUD COMPUTING IN PAPUA NEW GUINEA

The use of Information Communication Technology and Digital Technology started since 1990s. In Papua New Guinea, both the private sector and government organizations are using ICT and DT platforms such as cloud computing, AI and other technologies to enhance their strategic business objectives. In fact, organizations who build their planning and implementation models around ICT and DT seem to thrive and remain relevant where competition is high especially for businesses as well as effective service delivery for service-oriented organizations like government organizations. Digital government is the use of ICT to improve the efficiency and effectiveness of public sector operation and service delivery; or alternatively, the use by governments of ICTs to transform relations with citizens, businesses, and within government. Digital Government promotes and improves stakeholder contributions to development, as well as deepens the governance process (DICT, 2020).

The National Government of PNG (GoPNG) Digital Transformation Policy provides guidance and direction to PNG government departments and agencies on using the Government Cloud Infrastructure. It aims for efficient, secure, and sustainable cloud service consumption. The Department of Information Communication and Technology (DICT) is mandated to coordinate cloud services, data exchange, and shared services. The DICT is establishing a cloud platform for national and provincial government departments, including the DOWH. The "Cloud First" approach will help departments access current and emerging technologies to digitize their operations.

2.1 The Asset and Work Manager

The Asset and Work Manager is a cloud based world-class digital asset and work management solution that connects stakeholders in one seamless, single source of truth solution. It is a geospatial, real-time system supporting data accuracy and validation, making it possible to manage and maintain any asset class and type, in any location, at any time (thinkproject, 2025).

The system was introduced to the Department in 2022 and is currently in its second phase of development with 3 years remaining before the program becomes fully functional. At the conclusion of its development, the system is envisaged to perform the following key tasks; Systems Management, Network Management, Asset Management, Forward Works Programme Management, Pavement Management, Road Structures Management, Works Management, Emergency Management, Drainage Management, Safety Management and Asset Valuation. Performing these tasks require massive amount of data to be first uploaded into the system with the inbuilt analytical tools like HDM4 and GIS producing the expected results. This can only be facilitated through the cloud digital platform which the AWM system provides.

2.2 AWM Cloud Platform

This section will discuss various key features of the AWM system hosted on cloud platform. The AWM cloud platform provides cloud storage services which offer a scalable, security-rich and cost-effective home for the massive road data. The digital platform in adjustable in terms of capacity and optimize performance as requirements change. AMW also provides databases and integrations to support building or migrating a wide range of application and database types like videos, images, text and others. For example, our technicians use gadgets like GoPro cameras to capture high resolution images and videos or the TotalPave phone application to pick up IRI data which can be easily uploaded to the database in its different formats. Another key attribute to the AWM system is its analytics functions. Various applications such as the bridge management software, monitoring and evaluation function or HDM4 analyze the data and produce required results which is used to guide decision

making in network planning. Other cloud capabilities will be incorporated as the AWM system advances in the future.

Figure 2 below shows the basis architecture of the AWM system with current and future development expectations. Note that the source is from internal document between DOWH and the system's developer. Access to the source can be through DOWH.

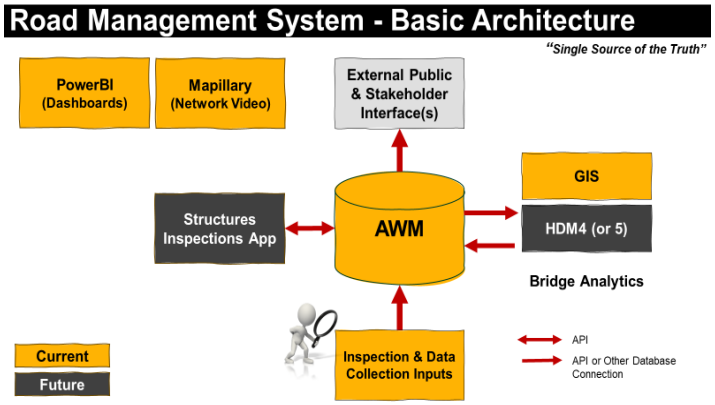

Figure 2 Basic architecture of AWM system *(Gough, 2025)*

3. IMPACT OF CLOUD COMPUTING IN DOWH

The Department of Works and Highways is Papua New Guinea's leading government agency responsible for developing, managing, and maintaining the nation's road and transport infrastructure including building infrastructure such as hospitals and schools. As the backbone of economic growth and social connectivity, DOWH ensures that every citizen has access to safe, reliable, and sustainable transport networks. To ensure effective implementation of the department's goals or objectives, the use of the ICT and DT is crucial. Basic types of ICT and DT services used in the organization include intranet, website, cloud technology, servers and data storage facility for road and bridge data such as condition surveys, design information, road and bridge inventory and so forth.

The Department is embracing cloud computing as part of the broader PNG Government Cloud Policy. This policy aims to streamline government operations by utilizing cloud services for infrastructure and software as a service. The Department of Information and Communications Technology (DICT) is responsible for coordinating the implementation of the cloud platform for all government departments, including the DOWH. The impact of Cloud Computing in DOWH particularly through the implementation of its road projects and programs is critical. It includes enhancing infrastructure through ICT, improving project management efficiency, and strengthening governance and accountability. The program leverages technologies like GIS, real-time reporting, and automated systems to track progress, identify bottlenecks, and ensure projects stay on schedule and within budget. The diagram below illustrates a typical could platform.

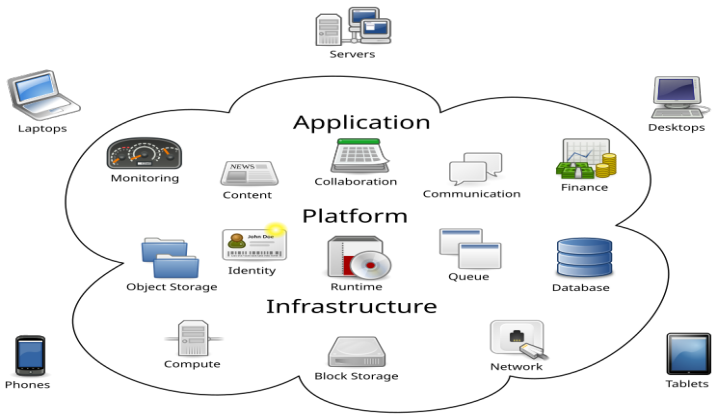

Figure 3 Overview of loud computing, with typical types of applications supported by that computing model (Johnston, 2020).

Four key impact areas cloud computing is having in DOWH is as follow;

1. **ICT Enhancement of Infrastructure**

   DOWH is integrating ICT into its operations to improve infrastructure development and maintenance. This includes using Road Asset Management Systems (RAMS) and Bridge Asset Management Systems (BAMS) to optimize resource allocation and make data-driven decisions. Note that both the RAMS and BAMS systems have been integrated to one system called the Asset and Work Manager. Having road and bridge inventory together with other relevant data sets like traffic volume, safety, pavement, structure and others ensures effective network planning.

2. **Project Management Efficiency**

   Digitalization of procurement processes and project dashboards, along with the integration of Internet of Things-enabled monitoring systems, are streamlining workflows and providing real-time project tracking. Projects reports uploaded on site using android phones or tablets with inbuilt reporting templates onto AWM cloud server from the provinces and accessed by Headquarter to prepare reports for senior management and the government including relevant stakeholders.

3. **Governance and Accountability**

   The program uses GIS and real-time reporting tools to track project progress, identify bottlenecks, and ensure projects stay on schedule and within budget. Regular audits and compliance checks are conducted to uphold financial integrity and operational efficiency. In the past records are kept in hard copies or sometimes in electronic format but with different people. The AWM system enables all project reports including design information, contract agreements and other critical information to be easily stored and accessed, hence improving and promoting accountability.

4. **Capacity Building**

   DOWH is investing in training programs to upskill its workforce in modern engineering practices and equip them with digital literacy. The cloud digital platform is a new technology that is making its way into PNG and DOWH although its existence dates back means that DOWH technicians must be knowledgeable to run the system, hence contributing to achieving the department's objectives or goals.

   Note that while the focus of this case study is mostly on the impact of cloud platform on the engineering side of things, other operational functions of ITC have also been impacted by cloud. For example, the government's financial management system called the Integrated Financial Management System (IFMS) is fully automated and is done one line today as opposed to manual processing in the past which is labor intensive and time consuming, thus delaying service delivery. The Government of Papua New Guinea

(GoPNG) is using digital transformation to change public administration processes, culture, and citizen experiences using information and communications technology (ICT) advancement as an enabler (DICT, 2020). The impact of cloud computing in DOWH is significant and it looks to advance even further in the future which means the department must be prepared to adapt with the evolving digital technology.

4. CHALLENGES OF CLOUD COMPUTING IN DOWH

Despite the progress made in the use of ICT and DT, significant challenges remain in effectively adopting technology into workplace such as digital divides, inadequate digital literacy, and insufficient professional development for professionals are common barriers. These barriers emphasize the importance of high-speed internet, and ongoing training and development opportunities for professionals, which are crucial for the effective use of ICT and DT in undertaking their day to day work. Professional organizations must prioritize addressing these gaps through targeted investments in infrastructure, professional development, and digital literacy initiatives (Kennedy, 2025).

Cloud computing adoption in PNG's Department of Works and Highways faces several challenges, including lack of planning, limited expertise, and security concerns. These challenges are compounded by the department's unique context in PNG, such as budget constraints, environmental pressures, and the need to adapt to changing workforce structures. These challenges are explained below.

1. **Lack of Planning and Expertise**
   Many cloud implementations fail due to inadequate planning and a lack of expertise within the department. This includes insufficient training for employees and a lack of clear understanding of how cloud services can be best leveraged for infrastructure projects.

2. **Security Concerns**
   Cloud security is a major concern, especially with sensitive infrastructure data and projects. Ensuring data protection, compliance with relevant regulations, and mitigating cybersecurity threats are crucial for successful cloud adoption.

3. **Inadequate Internet accessibility to all 22 provinces**
   Internet accessibility to all 22 provinces of PNG is not efficient and sustainable as cloud platforms depends on it. Setting up infrastructure in all provinces remains an ongoing challenge.

4. **Budget Constraints**
   Limited government funding can hinder the implementation of cloud infrastructure and delay critical infrastructure projects, requiring innovative solutions to optimize resource allocation.

5. **Environmental Factors**
   PNG's unique geographical and environmental conditions, such as its rugged terrain and susceptibility to natural disasters, necessitate the integration of climate-resilient designs into infrastructure planning and construction, which may require specialized cloud-based tools and expertise.

6. **Workforce Adaptation**
   The department's evolving role from direct service delivery to a supervisory and regulatory body, as well as the adoption of outsourcing models, requires adapting to new technologies and ensuring contractors adhere to national standards using cloud-based solutions.
   The introduction of cloud technology in the modern age requires the department to keep up with the knowledge trend in terms of upskilling its manpower and being creative in finding solutions to the challenges so that it can continue to operate it and remain relevant with the rest of the world.

5. OPPORTUNITIES OF CLOUD COMPUTING IN DOWH

Despite the challenges covered in the section before, cloud computing offers significant opportunities for the Department of Works and Highways (DOWH) to improve efficiency, enhance project management, and streamline operations. Key areas include leveraging cloud-based platforms for improved road network planning, real-time project monitoring, facilitating secure data exchange between agencies, and enabling remote access to critical information, ultimately contributing to better service delivery and citizen engagement. These opportunities are presented as follows;

1. **Road Network Planning**
   The utilization of cloud platform to store and manage road data is crucial. Road and bridge data collection using relevant software and field-based applications, design software, accessing data remotely through cloud. Analytical applications dissect and analyze data to inform and drive business decision making, in this case the government can be better guided in terms of providing budget for road development and maintenance programs.

2. **Project Management & Monitoring**
   Implement cloud-based project management tools to track progress, manage budgets, and ensure accountability across all projects. The AWM system has inbuilt monitoring and evaluation function which ensures field engineers to update project reports using field-based applications downloaded onto tablets and upload to the main cloud platform which is then analyzed and automatically produces consolidated reports for senior management within DOWH and GoPNG.

3. **Data Sharing and Collaboration**
   Utilize cloud services to facilitate secure data exchange and collaboration between different government agencies and stakeholders involved in infrastructure projects, promoting interoperability and reducing duplication of effort. The sharing of information will ensure proper planning for maximum social and economic output. Through the AWM system, its cloud platform will enable other government departments to have access to the road network development plans for the long term and can integrate their plans accordingly. For example, the Department of Agriculture can plan their investment in parts of the country where the road network is developing.

4. **Remote Access & Accessibility**
   Enable remote access to road data, project data, policies, and development and maintenance plans for DOWH staff and the public, enhancing transparency and accessibility.

5. **Smart Infrastructure & Real-time Monitoring**
   Introduce smart infrastructure systems, including sensors and monitoring tools, to track road conditions and usage in real-time, ensuring timely maintenance and optimizing resource allocation.

6. **Digital Transformation**
   Embrace the "Cloud First" approach to leverage current and emerging technologies to further enhance and digitize DOWH processes and operational mandates.

7. **Cost Reduction**
   Reduce ICT investment costs by utilizing the Government Cloud Platform, a sanctioned platform for government departments to deploy cloud solutions. Cloud platform handle much of the infrastructure management as this is common in managing on premise servers, thus freeing up IT staff to focus on other tasks.

8. **Enhanced Service Delivery**

Improve service delivery to citizens by providing real-time updates on project status, enabling public feedback, and making key information easily accessible.

The opportunities discussed in this part of the study proves that the department can harness them into achieving its objectives. The government investment in roads has always been a challenge in terms of justifying its social and economic benefit. Today, road data is collected, stored and analyzed aided by cloud platform to ensure evidenced based decision-making, therefore yielding high social and economic returns for the country and its people.

6. CONCLUSIONS

Joseph Carl Robnett Licklider is considered to be the father of cloud computing. In 1960, he developed ARPANET, a precursor to the internet. By developing ARPANET, he introduced the concept of time sharing where multiple users share computing resources. This groundbreaking invention has now given businesses including government organizations the competitive edge to store and manage their data which is then used to guide them in making sound business decisions ensuring objectives or goals are met.

The Department of Works and Highways is also embracing the cloud platform in storing and managing its road data as well as facilitating its operational requirements like financial management system and HR system. Choosing which road to invest in may seem an easy decision for the National Government of PNG to make because these days everyone needs a road, however given the resource constraints, not all roads can be built any one time. It calls for strategic network planning where roads based on its high social and economic value is most likely to be considered first then the others. Transport economics is based on the idea that the economic return on a road built is used to build another new road. A branch of this concept also states that sustaining the existing network through regular maintenance is critical as it is already generating revenue for the country. Wise thinking would recommend sustaining the existing network to developing a new one. But the question remains, how does one make these investment decisions? The answer is simple, what does the data tell you?

In the past, the Department of Works and Highways has had no proper road data storage and management mechanisms with proper analytical tools or software to analyze the raw data to guide the important investment decision making. This prompted the department to adapt the Asset and Work Manager system. A key feature of this system is that it is operates on a cloud platform which practically solves all the problems for road network planning in DOWH. Having 22 provincial establishments around the country and managing almost 30,000km of both national and provincial roads, the cloud platform provides the environment where data can be uploaded or accessed remotely. Analytical tools such as RAMS, BAMS and HDM4 are inbuilt into the system where the raw data can be analyzed to produce expected results. Additional software depending on the complexity of task can be integrated into the system, thus making the network planning more efficient than ever.

The cloud platform has brought about many opportunities such as improving access and collaboration, increase flexibility and scalability, enhancing security and reducing cost. However, just like any new digital technology, there are challenges that the department must address such as lack of expertise, poor internet accessibility, data security threats, budget constraints and others. These challenges can be solved through creative thinking, capacity development, collaboration with cloud service providers such as PNG DataCo, improve internet accessibility and open dialogue with all stakeholders.

This study has been able to discuss the key objectives in terms of the impact, challenges and opportunities of cloud computing in the Department of Works and Highways. I have also provided an insight into the Asset Work Manager system which is the backbone of network planning aided by cloud platform. The use cloud and other digital technologies is here to stay with further developments and advancements expected in the future, therefore the department must remain receptive to the changes and will use the technology to its advantage while at the same time managing the challenges.

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