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# Assessing the Water Balance and Groundwater Drying Trends in Papua New Guinea: The Potential of Soil and Water Conservation for Recharge Restoration

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**Abstract:** Groundwater stress is becoming more prevalent in Papua New Guinea, particularly in rural and peri-urban areas where shallow aquifers are essential for subsistence. This study does a quantitative water balance assessment to better understand the causes of these drying trends. The research looks into the imbalance between recharge and outflow rates in critical regions of PNG by assessing climatological and hydrological data such as rainfall, evapotranspiration, surface runoff, and groundwater extraction. Furthermore, the study assesses the effectiveness of soil and water conservation (SWC) techniques in mitigating aquifer depletion. Contour farming, vegetative cover, recharge ponds, and check dams are all being considered for their ability to improve groundwater recharge rates. Preliminary findings suggest that implementing targeted SWC treatments, particularly in highland and deforested areas, can dramatically increase groundwater recharge capacity. Finally, the study makes practical recommendations for incorporating SWC methods into local watershed and water resource management programs. This attempts to manage rising groundwater stress and maintain the long-term usage of this critical resource in Papua New Guinea.

**Keywords:** Groundwater; Water Balance; Recharge; Soil and Water Conservation (SWC); Papua New Guinea (PNG)

## Author Biography:

Dr. Mirzi Betasolo holds a PhD in Technology Management and a Master of Engineering in Civil Engineering with specialties in structural, water resources, and environmental engineering. She is a licensed Civil and Geodetic Engineer in the Philippines with over 26 years in education and 20 years in practice. Her work spans river modeling, drainage systems, procurement policies, and tunnel viability studies, making her a research leader in PNG's civil engineering community. Dr. Betasolo is a member of IEPNG, ACIGS, ASTM, PICE, GEP, and SWE. She serves as a SWE Ambassador for Papua New Guinea on several occasions since 2018.

## 1. INTRODUCTION

Accessible freshwater comes from streams, lakes, and underground sources [Downing et. al.]. The Papua New Guinea may experience a scarcity of water which is needed to meet the population and industrial needs [Jensen et. al.]. Thus, ground water can be mentioned as precious natural assets that support economic development and ecological diversity [Downing et. al.]. Flow dynamics of lakes is dependent on groundwater level, which is given a current focus globally [Ajami, Ala-aho et. al.]. Therefore, measures should be taken to rehabilitate and manage vulnerability of the lakes. Groundwater is often withdrawn to support man's activities that will support life such as use in agricultural activities, the industries in preparing their goods and households in the municipalities and cities by operating extraction wells which in the long run exhaust the resource [Fan et. al.]. The measures must rescue the water ecology, dependent farming systems and contribute to the economy [Kløve et. al.]. The analysis of water balance is one of the methods to determine the groundwater inflow [Batelaan et. al.]. Temperature increment and unreliability of precipitation may not be the only factor to vary the lake water balance, both natural and anthropogenic activities affecting the fluctuation of water depth over time. Balancere, analyzing the lake water

balance through proper techniques will be essential for the establishment of mitigation strategies. Therefore, this study aims to bridge this gap by combining water balance assessment with evaluation of SWC potential in restoring groundwater recharge in selected areas of PNG. Unregulated extraction can lead to lowered water tables, reduced well yields, increased pumping costs, and potential saltwater intrusion in coastal areas [White et. al.]. Hence, the groundwater holds immense significance for Papua New Guinea, particularly in rural areas where it frequently serves as the most reliable and safest source of freshwater [Bourke et. al.]. Moreover, in some regions, particularly during prolonged dry seasons and El Niño events, communities relying on shallow wells and springs are experiencing water shortages, indicating a potential decline in local groundwater tables [Allen et. al.]. Sustainable management and protection of these vital groundwater resources are therefore crucial for the well-being and development of rural Papua New [Alamgir et. al.]. Furthermore, environmental impacts from mining and inadequate waste management practices pose a threat to groundwater quality, potentially reducing the availability of usable groundwater [Schofield et. al.]. The increasing demand for freshwater due to population growth, agricultural expansion, and industrial activities in Papua New Guinea necessitates the sustainable management of groundwater resources to prevent depletion [Carrard et. al.]. Thus, there is a greater influence on groundwater quality, water balance, discharge, and ecology of lake during the study of wetlands and groundwater fed lakes that the water level fluctuation in such regions has an effect on the shallow lakes that highly depend on the ground water discharge [Teweldebrihan et. al.].

Water balance studies are essential for quantifying inflows, outflows, and storage changes in a hydrological system. They offer insight into managing freshwater resources, planning for agriculture, and predicting the effects of climate variability. In tropical and arid areas alike, soil water content plays a key role in vegetation, nutrient cycling, and runoff regulation. In PNG, these dynamics are poorly monitored, requiring further research and modeling. To address this, PNG needs a groundwater-specific management framework that integrates hydrological science, traditional knowledge, and community engagement. SWC methods can serve as an entry point for such a framework, delivering co-benefits for climate adaptation, food security, and public health. Capacity-building and investment in monitoring infrastructure are essential. Several examples from Southeast Asia and Sub-Saharan Africa illustrate the success of soil and water conservation (SWC) in boosting groundwater recharge. In Ethiopia's Tigray region, stone bunds and trench systems led to a 30–60% increase in soil moisture and groundwater levels. In India's Maharashtra state, check dams and farm ponds helped reverse declining water tables within a decade. These low-tech solutions demonstrate potential for application in PNG's diverse terrain. In Papua New Guinea, pilot efforts in the Highlands have introduced vetiver grass strips and gully plugs to reduce erosion and increase infiltration. Although under-documented, anecdotal reports from agricultural officers suggest visible improvements in soil retention and well reliability in trial villages. A formal monitoring framework could scale these efforts with data-driven targeting.

The purpose of this study is to examine the water balance and groundwater drying trends in PNG by examining climatological and hydrological data to better understand the imbalance between recharge and outflow rates. It also looks into how soil and water conservation techniques like contour farming and recharge ponds might help with groundwater recharge. Therefore, the review study findings indicate that implementing targeted SWC strategies, particularly in highland and deforested areas, can dramatically increase groundwater recharge capacity, providing practical recommendations for sustainable water resource management in Papua New Guinea.

## **2. LITERATURE REVIEW**

The groundwater studies in Papua New Guinea (PNG) and the wider Pacific region have been crucial in understanding the availability, quality, and sustainability of this vital resource for island communities [White, Bourke, Carrard et. al.]. These studies have highlighted the generally good groundwater potential in many parts of PNG, while also identifying complexities related to hard rock aquifers and the need for integrated approaches in resource evaluation [Wambrauw]. Across the Pacific, a significant focus has been on the unique hydrogeology of small island states, particularly atoll islands, where thin freshwater lenses are vulnerable to saltwater intrusion due to over-pumping and rising sea levels [White et. al.]. Consequently, regional studies have also aimed to develop consistent hydrogeological classifications that show different climate scenarios on island groundwater sustainability, emphasizing the critical role of groundwater for both ecosystems and human populations in the Pacific [Sapala et. al.]. As a result, the interaction of surface-groundwater would affect the quality, ecology,

biology and chemistry of lake water [Fleckenstein, Green et. al.]. Groundwater serves as a vital source of drinking water, especially in rural communities, and supports ecosystems [Griebler et. al.]. However, recent field observations and community reports indicate that wells and springs in parts of the Highlands and coastal regions are experiencing lower yields and seasonal drying, attributed to both climatic variability and land use change. Globally, water balance models have proven effective in diagnosing regional hydrological stress by quantifying inputs (precipitation), outputs (evapotranspiration, runoff), and changes in storage (groundwater). In parallel, the adoption of soil and water conservation (SWC) techniques has been widely promoted in Sub-Saharan Africa and Southeast Asia as a sustainable solution for enhancing water infiltration and reducing surface runoff [FAO, Rockström et. al.].

Research in these contexts has explored sustainable extraction methods like horizontal wells and infiltration galleries, alongside assessments of aquifer vulnerability to climatic variations and anthropogenic contamination [Machiwal, Banerjee et. al.]. Most lakes generally receive inflow from groundwater through their bed laterally or vertically via seepage from the aquifer [Poff et. al.]. Hence, understanding SWC dynamics is crucial for drought monitoring, land degradation assessment, and developing strategies for water-scarce agriculture [Teweldebrihan et. al.]. Despite the nation's high annual rainfall—often exceeding 2,000 mm in many regions—groundwater resources have increasingly shown signs of stress, particularly in areas with growing population pressure, land degradation, and limited infrastructure for sustainable water management. Studies in PNG have largely focused on surface water hydrology, with limited data available on long-term groundwater monitoring [Wambrauw]. These include contour bunds, mulching, afforestation, and check dams—all of which contribute to increased groundwater recharge. While SWC practices have been promoted in PNG's agricultural development programs, their hydrological impact remains under-explored [Prentice et. al.].

### 3. MATERIALS & METHODS

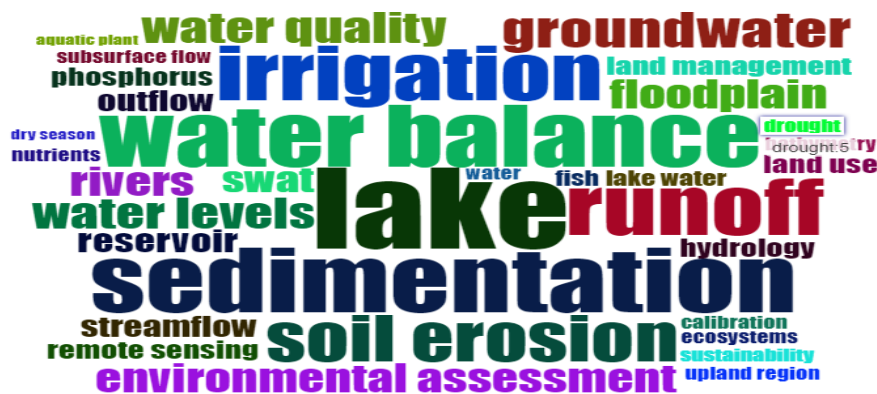
The methodology combined meta-analysis of relevant hydrological studies with trend analysis using secondary datasets. Literature was sourced via Web of Science and Scopus, focused on PNG's groundwater, climate, and conservation, and groundwater extraction. SWC methods were evaluated based on their recharge potential, drawn from both regional and international case studies.

The primary source involved leveraging a previously published systematic review database [Sapala et. al.], which specifically focused on PNG and provided an extensive collection of relevant literature, including studies pertinent to the PNG Potential of Soil and Water Conservation (SWC) for Recharge Restoration and its catchment. However, recognizing that this PNG-centric database might lack broader basin-wide information, a supplementary, customized literature search was executed. This secondary search utilized prominent online scientific article search engines, namely Scopus and Web of Science ([www.webofscience.com](http://www.webofscience.com)). The search strategy employed two categories of terms: firstly, terms directly referencing the Water Balance and Groundwater Drying Trends in Papua New Guinea, such as “PNG groundwater,” “PNG water balance,” “soil and water conservation,” “Recharge,” “Restoration,” “PNG surface water,” “River,” “Lake,” and “water balance.” Secondly, terms related to specific Water-Energy-Food-Ecosystem (WEFE) [Abera et. al.] components relevant to the basin were utilized, including “PNG groundwater,” “groundwater trend,” “PNG river basin,” “groundwater drying trend,” “Nexus,” “WEFE,” “WFE,” “Food,” “Water,” “Energy,” “Ecosystem,” “Environment,” “water volume,” “water quality,” “hydrology,” “water balance,” “climate change,” “Livelihoods,” “Agriculture,” “aquatic ecosystem,” “groundwater,” “human impact,” “rainfall trend,” “climate change,” “hydrochemical,” “physicochemical,” “groundwater trend,” “surface water trend,” “evapotranspiration,” “river inflow,” “fauna,” “flora,” “watershed,” “catchment,” “basin,” “water resource,” and “irrigation.” This meticulous dual-pronged approach ensured a comprehensive collection of literature, effectively covering both the spatial and thematic dimensions of Water Balance and Groundwater Drying Trends issues within Papua New Guinea.

### 4. RESULTS & DISCUSSION

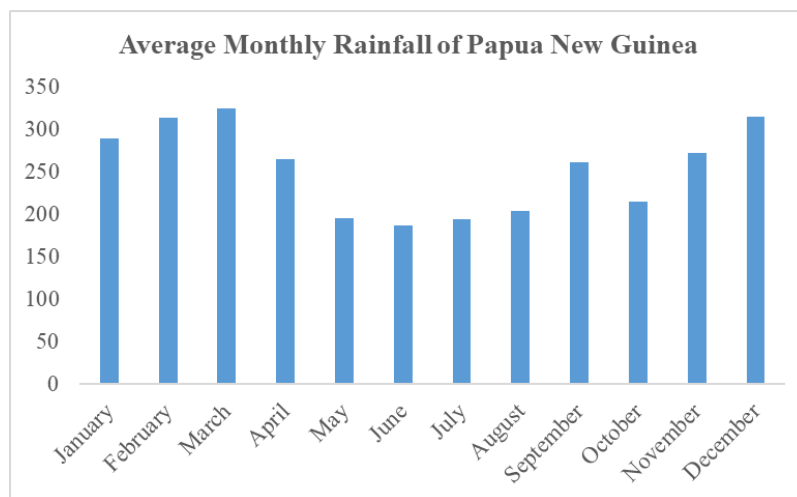
Meta-analysis of 125 studies emphasized recurring themes: falling groundwater tables, decreased spring yields, and dry wells. Soil and water conservation (SWC) techniques like contour bunds, vegetative strips, and check dams have shown success in improving infiltration and restoring water balance. In PNG, where deforestation and

shifting agriculture are prevalent, these methods can stabilize soil and improve aquifer recharge. As illustrated in Figure 2, the thematic focus of these investigations was primarily decided by the authors' keywords. The most regularly used terms included "water balance," "lake," "runoff," "irrigation," and "sedimentation." This significance stems from a strong research focus on the hydrological cycle, surface water dynamics, and human interventions (such as irrigation) that have a direct impact on water supply and quality. Moreover, other relevant keywords, such as "soil erosion," "water quality," "groundwater," "environmental assessment," "sustainability," "water levels," "Groundwater Drying Trends," and "rivers," emphasize the interconnection of these issues. The collective use of these terms suggests that scientific attention has been primarily directed toward understanding the intricate interactions between terrestrial and aquatic ecosystems, recognizing their profound interconnectedness, especially in the face of changing climatic conditions and land use practices affecting water resources in Papua New Guinea.



**Fig 1.** A word cloud including the author's selected keywords from the meta-analysis publications. Each word's size and prominence correspond to how frequently it appears in the selected articles.

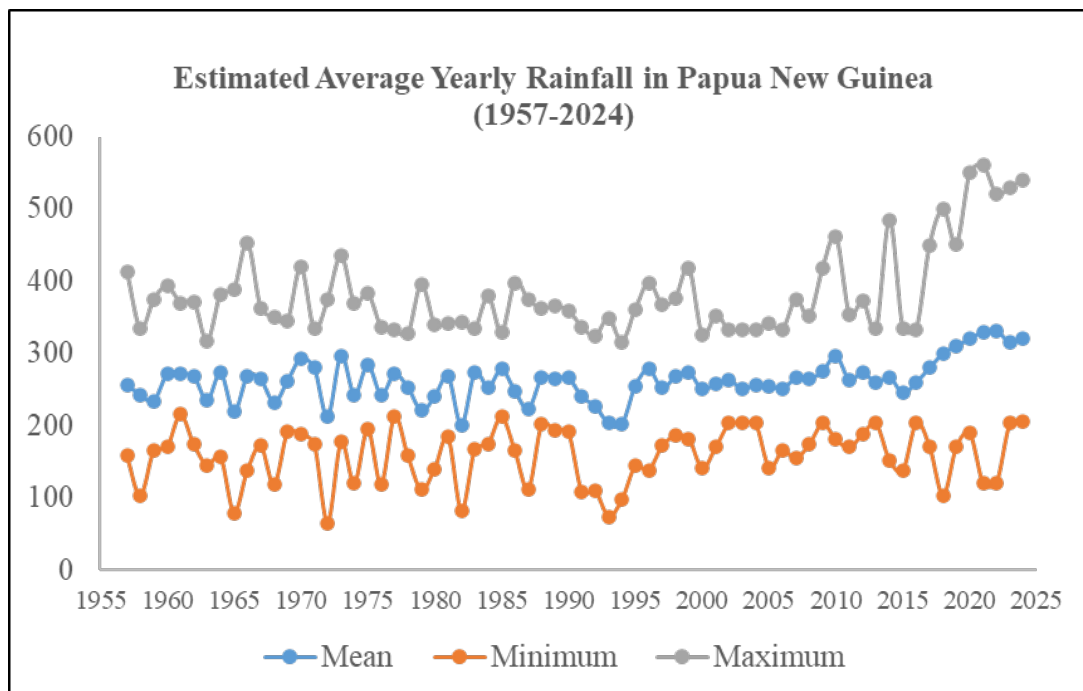
Analysis of climatological and hydrological data shows a mismatch between rainfall patterns and groundwater recharge. PNG's rainfall has a bimodal distribution, with peaks in March and December, and drier periods from May to August as shown in Fig 2. However, increasing groundwater extraction and land-use changes reduce infiltration, especially in highland and coastal regions.



**Fig 2.** Papua New Guinea rainfall – monthly average

The Fig 3 on next page depicts the average yearly rainfall from 1957 to 2024, which remained within an approximate range of 170 mm to 500 mm. Interestingly, while the bold blue line representing year-to-year changes shows periods of increase and decline, the overall trend line (represented by the dotted black straight line) for both precipitation and groundwater levels reveals a noticeable growing trend over this extended period. Thus, the blue

dots represent the yearly average rainfall, with the maximum annual average rainfall recorded in 2012 at 274 mm. This thorough temporal analysis emphasizes the dynamic character of PNG's hydrological patterns, as well as the current surge in scientific research targeted at understanding and tackling these critical environmental issues.

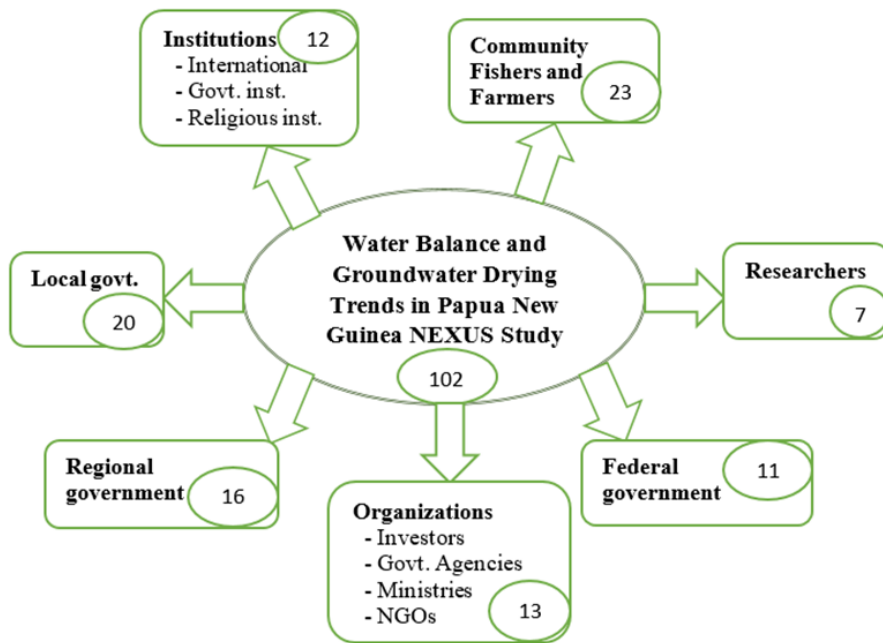


**Fig 3:** A review of Papua New Guinea's anticipated rainfall pattern from 1957 to 2024.

Stakeholder analysis highlighted key actors: local communities, provincial governments, NGOs, and academic researchers. Local ownership and capacity building are vital for sustainable SWC implementation. Incorporating SWC into local watershed and climate adaptation policies can provide long-term benefits.

The sophistication and range of methodological techniques in academic inquiry have grown significantly over time, particularly during the second half of the 2000s. Prior to the 2000s, research relied heavily on confirmatory and inferential analysis, aiming to establish links and draw conclusions from observable data. This foundation eventually evolved toward more robust numerical and physical-based modeling, which enabled more precise simulation and prediction of complex processes. Following that, a shift happened toward geospatial-based analysis, which uses spatial data and technologies to discover patterns and correlations across geographic areas. Despite these significant methodological advances, there is still a significant gap in the broad adoption of nexus-based analysis. While promising, just a few recent research has used this comprehensive approach, and it has yet to emerge as a common tool for analyzing interrelated systems.

The review study on the Water Balance and Groundwater Drying Trends in Papua New Guinea NEXUS demonstrates a stakeholder analysis in which various articles identify entities involved and their respective numbers of research studies, presumably representing individual participants or relevant entities within each category (Fig 4).



**Fig 4.** Stakeholder's involvement in the WEF-NEXUS studies

The primary issues of the "Water Balance and Groundwater Drying Trends in Papua New Guinea NEXUS Study" are central to this study, with 102 articles chosen from the 250 papers obtained for the review study that are closely related to the study. Several significant stakeholder groups have been found around this core in various research. According to 23 articles, "Community Fishers and Farmers" are an important group, emphasizing the importance of grassroots participation and the direct influence of water trends on livelihoods. On the other side, 20 articles titled "Local government" account for the critical role of local administrative authorities in tackling these concerns. Thus, around 16 research show that "regional government" follows, emphasizing the need for a multi-tiered governmental system. Furthermore, 13 articles focusing on "Organizations" include a varied range of entities such as investors, government agencies, ministries, and NGOs, implying a coordinated effort across many organizational levels. "Institutions," which include international, government, and religious organizations, has 12 articles, indicating the involvement of established bodies with greater reach and influence. Finally, 11 studies show that "Federal government" has, indicating national-level engagement, and "Researchers" with 7 articles are critical for giving scientific expertise and analysis to the study. This schematic diagram successfully illustrates the study's multifaceted nature, emphasizing the importance of collaboration and input from a diverse range of stakeholders in addressing water balancing and groundwater drying trends in Papua New Guinea.

## 5. CONCLUSION & RECOMMENDATIONS

Groundwater drying trends in Papua New Guinea pose serious risks to water security, especially in rural and highland regions. Despite high annual rainfall, localized depletion is rising due to land-use changes, population pressure, and inadequate recharge. This study shows that soil and water conservation (SWC) techniques can significantly improve groundwater recharge.

We recommend prioritizing SWC strategies in water-stressed regions, supported by hydrological monitoring and stakeholder collaboration. Further integration into development plans and climate resilience policies is essential for ensuring sustainable water supply in PNG.

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