

Assessing the Impact of Land Use Change on Groundwater Dynamics in the Mati Watershed Using SWAT+ Model

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ABSTRACT : Rapid urbanization and land transformation in southern Bali have profoundly disrupted the hydrological balance of the Mati Watershed. The conversion of agricultural and vegetated areas into built-up and commercial zones has increased surface runoff while decreasing groundwater infiltration and recharge, leading to deeper groundwater tables, declining aquifer capacity, and greater risks of flooding and water scarcity. This study aims to assess the impacts of land use change on groundwater dynamics between 2017 and 2024 using the Soil and Water Assessment Tool Plus (SWAT+). Key parameters analyzed include aquifer storage, groundwater depth (dep_wt), recharge (rchrq), and seepage (seep), with a focus on identifying sub-basins experiencing groundwater depletion or hydrogeological resilience. The research utilizes multi-source data such as Sentinel-derived land use maps 2017 and 2024, FAO soil data, an 8.25 m DEMNAS Digital Elevation Model, river network data from BWS Bali–Penida, and meteorological data from BMKG, processed using QGIS 3.34 and SWAT+ Editor. Simulations for 2017 and 2024 were compared to evaluate hydrological shifts driven by land use change. Despite the absence of model calibration due to limited field data, the results reveal substantial decreases in aquifer storage, recharge, and seepage, along with a deepening of the groundwater table. The conversion of vegetated and agricultural land into built-up and rangeland areas has disrupted the natural balance between infiltration and runoff, causing systemic degradation of groundwater resources. Nevertheless, Sub-basin 22 demonstrates relative resilience, maintaining higher aquifer storage, stable groundwater levels, and stronger recharge potential due to favorable geomorphological and soil characteristics.

KEYWORDS - Watershed, land use change, groundwater, QGIS, Sentinel

I. INTRODUCTION

Rapid urbanization and land use transformation have become defining features of many tropical watersheds [1], [2], including those in southern Bali [3]. The Mati Watershed which spans parts of Badung Regency and Denpasar City—has experienced extensive conversion of agricultural and vegetated areas into built-up and commercial zones driven by tourism, housing development, and socio-economic growth. This transformation alters surface characteristics, reduces infiltration capacity, and accelerates surface runoff, ultimately disrupting the natural hydrological cycle. The resulting imbalance between infiltration and runoff has led to declining groundwater storage, deepening of the water table, and an increased risk of urban flooding [4], [5], [6], particularly in low-lying areas such as Kuta, Seminyak, and Sunset Road. Such hydrological shifts threaten the sustainability of both ecological systems and water supply networks in this rapidly urbanizing watershed. This study focuses on assessing these dynamics within the Mati watershed from 2017 to 2024, emphasizing how land use changes influence aquifer storage, groundwater depth, and recharge–discharge processes that sustain water availability in the region. Previous studies on hydrological change in Bali have largely focused on surface hydrology, including runoff, sediment transport, and flooding, with limited emphasis on subsurface processes [7], [8]. Research on Mati Watershed has primarily addressed urban flood management and drainage system design, while the quantitative assessment of groundwater dynamics—such as aquifer storage, recharge, seepage, and water table depth—remains scarce. Moreover, there is limited spatially detailed analysis that connects land use change with groundwater responses at the sub-basin scale. This knowledge gap constrains efforts to design integrated watershed management strategies that address both surface and subsurface water interactions, particularly in highly urbanized, low-permeability catchments like Mati where agricultural and traditional irrigation systems coexist with dense urban infrastructure. Recent advancements in hydrological modeling, particularly the Soil and Water Assessment Tool Plus (SWAT+), have made it possible to simulate both surface and subsurface hydrological processes with greater precision [9], [10], [11], [12]. The SWAT+ model allows for flexible spatial discretization, improved linkages between groundwater and surface water, and dynamic representation of land use change scenarios.

Studies in tropical environments have shown that SWAT+ is highly effective for assessing groundwater recharge, storage variation, and the impacts of land conversion on watershed-scale hydrodynamics. Building on these capabilities, this research applies SWAT+ to the Mati watershed to model multi-year changes (2017–2024) in groundwater-related parameters—specifically aquifer storage (stor), depth to water table (dep_wt), recharge (rchrg), and seepage (seep)—to better understand the hydrological consequences of rapid land use change. Groundwater depletion has become a critical environmental issue in Bali, particularly in the southern coastal regions where tourism-driven water demand continues to rise [13], [14]. In the Mati watershed, the reduction of permeable areas due to urban expansion, loss of agricultural land, and land compaction has significantly decreased the capacity for natural groundwater recharge. This imbalance between extraction and replenishment threatens long-term water security and ecological stability, while also exacerbating urban flood hazards during heavy rainfall events.

Without effective management, continuous aquifer depletion may lead to dry-season water scarcity, decreased baseflow to rivers, and potential saltwater intrusion in downstream coastal zones. Therefore, this study is urgently needed to provide empirical evidence and spatially explicit analysis that can inform sustainable groundwater management, urban planning, and climate adaptation policies for the Mati watershed. This study offers a novel contribution by integrating multi-temporal SWAT+ modelling with spatial analysis of aquifer and groundwater variables to evaluate the hydrological impacts of land use change in an urban–coastal watershed setting. Unlike previous studies that emphasize only surface runoff and flooding, this research bridges both surface and subsurface hydrology, providing a comprehensive understanding of watershed function. The study also identifies sub-basins with hydrogeological resilience, such as those with higher recharge and storage capacity despite land conversion pressures.

These insights can guide the designation of groundwater conservation zones and inform spatially adaptive management strategies to maintain hydrological balance under future urban development scenarios. This study represents an initial modeling assessment of groundwater and hydrological responses to land use change in the Mati Watershed using the SWAT+ framework. However, the model has not yet undergone a full calibration and validation process due to limited availability of observed hydrological and groundwater data within the catchment. Consequently, the simulated results presented in this study should be interpreted as relative trends and spatial patterns, rather than as absolute quantitative values. The primary aim of this research is to quantify and evaluate the impacts of land use change on the hydrological and groundwater dynamics of the Mati watershed from 2017 to 2024 using the SWAT+ model. This study specifically focuses on analyzing the spatial and temporal patterns of land use change and their correlation with key groundwater parameters, including aquifer storage, water table depth, recharge, and seepage. Furthermore, it aims to identify sub-basins that exhibit significant groundwater depletion or demonstrate hydrogeological resilience under changing land use conditions. The research also seeks to assess the integrated hydrological response of the watershed to anthropogenic and land use pressures, providing a comprehensive understanding of how urbanization and land transformation influence groundwater behavior.

II. RESEARCH METHODS

Research Location: This research was conducted in the Mati Watershed located in the southern part of Bali Island, Indonesia, spanning administrative areas within Badung Regency and Denpasar City. The watershed covers a mix of urban, agricultural, and coastal environments, extending from the upland regions in the north—characterized by mixed vegetation and agricultural lands—to the low-lying coastal plains in the south, which are dominated by densely built-up and commercial zones such as Kuta, Seminyak, and Sunset Road. The watershed is hydrologically significant due to its role in draining surface water from upstream catchments into the southern coast, where tourism, settlement, and infrastructure development exert substantial pressure on water resources. Its geographic position makes it particularly vulnerable to land use change, groundwater depletion, and flooding, making it an ideal case study for assessing the hydrological impacts of rapid urbanization on groundwater systems.

Research Data : This study integrates multi-source spatial and hydrological datasets to simulate and evaluate changes in groundwater and hydrological conditions from 2017 to 2024. The primary input datasets include:

1. Land Use Data for 2017 and 2024, derived from Sentinel imagery classification, used to capture the temporal transformation of land cover and urban expansion across the watershed.
2. Soil Data, obtained from the FAO soil database, providing information on soil texture, hydrological group, and infiltration characteristics essential for modelling infiltration and percolation processes.

3. Digital Elevation Model (DEM) data sourced from DEMNAS (Digital Elevation Model Nasional) with a spatial resolution of 8.25 meters, utilized for watershed delineation, slope analysis, and sub-basin boundary generation.
4. River Network Data, acquired from Balai Wilayah Sungai (BWS) Bali–Penida, which was used to define the drainage network and flow paths for hydrological routing within the SWAT+ model framework.
5. Meteorological Data, including rainfall, temperature, relative humidity, solar radiation, and wind speed, obtained from the nearest BMKG (Meteorological, Climatological, and Geophysical Agency) stations, providing climate forcing inputs for the simulation period.

All spatial datasets were pre-processed using QGIS 3.34, involving projection standardization to UTM Zone 50S (WGS 84), clipping to watershed boundaries, and reclassification for model compatibility. The temporal consistency of datasets was ensured through cross-referencing between 2017 and 2024 to maintain comparability across simulation years.

Research Analysis Methods : The hydrological and groundwater analyses were conducted using the Soil and Water Assessment Tool Plus (SWAT+), an advanced, semi-distributed, process-based model designed to simulate surface and subsurface hydrological processes at the watershed scale. The model was developed in the SWAT+ Editor interface and executed through the SWAT+ Toolbox. The watershed was divided into multiple sub-basins and hydrological response units (HRUs) based on the overlay of land use, soil, and slope classes to capture spatial variability in hydrological response.

Model simulations were performed for two main timeframes—2017 and 2024—representing pre- and post-land use change conditions. The model outputs analyzed included key groundwater-related parameters, namely:

- Aquifer Storage (stor) – representing the total volume of groundwater stored in the saturated zone, expressed in millimeters (mm).
- Depth from Surface to Aquifer Water Table (dep_wt) – indicating groundwater level or water table depth, expressed in meters (m).
- Groundwater Recharge (rchrg) – representing the amount of water percolating from the soil to the aquifer.
- Seepage Out of the Aquifer (seep) – describing subsurface water flow or discharge from the aquifer.

Each parameter was spatially mapped and statistically compared between 2017 and 2024 to evaluate the impacts of land use transformation on groundwater dynamics. The change detection approach was applied to quantify spatial differences and percentage variations across sub-basins. Visualization and interpretation of model outputs were carried out in QGIS and SWAT+ Output Viewer, emphasizing the identification of sub-basins exhibiting groundwater depletion or hydrogeological resilience.

While the model setup followed the standard SWAT+ procedures, it is important to note that model calibration and validation were not performed due to the limited availability of observed hydrological and groundwater data in the Mati watershed. Therefore, the analysis primarily focuses on relative spatial and temporal trends rather than absolute quantitative accuracy. Despite this limitation, the results provide valuable insights into the directional impacts of land use change on groundwater storage, recharge, and water table dynamics, serving as a scientific basis for further model refinement and field calibration.

III. RESULT AND DISCUSSION

The analysis from 2017 to 2024 reveals substantial hydrological and land use transformations within the watershed, as simulated using the SWAT+ model. The results demonstrate that extensive land use conversion—from vegetated and agricultural lands to built-up and rangeland areas—has significantly altered the watershed’s hydrological behavior, leading to decreased infiltration, reduced aquifer storage, deepened groundwater levels, diminished recharge, and lower seepage rates.

Land Use Change : Figure 1 illustrates significant land use transformation within the watershed between 2017 (Figure a) and 2024 (Figure b). In 2017, the watershed displayed a more heterogeneous landscape dominated by trees (green), crops (cyan), and rangeland (red), with scattered patches of water bodies and flooded vegetation—particularly in the central and northern sub-basins (Sub-basins 7, 11, 13, 15, and 22). This composition supported higher infiltration and groundwater recharge due to vegetative cover and permeable soil conditions.

By 2024, a marked expansion of built-up areas (magenta) and rangeland (red) replaced much of the vegetated and agricultural zones, especially in the central and northern portions of the watershed. Such land cover conversion from permeable (vegetated) to impervious (urban) surfaces has significantly reduced infiltration capacity, enhanced surface runoff, and decreased subsurface percolation to the aquifer. Consequently, these

changes have directly influenced the spatial dynamics of aquifer storage and groundwater levels, as evidenced in the following maps.

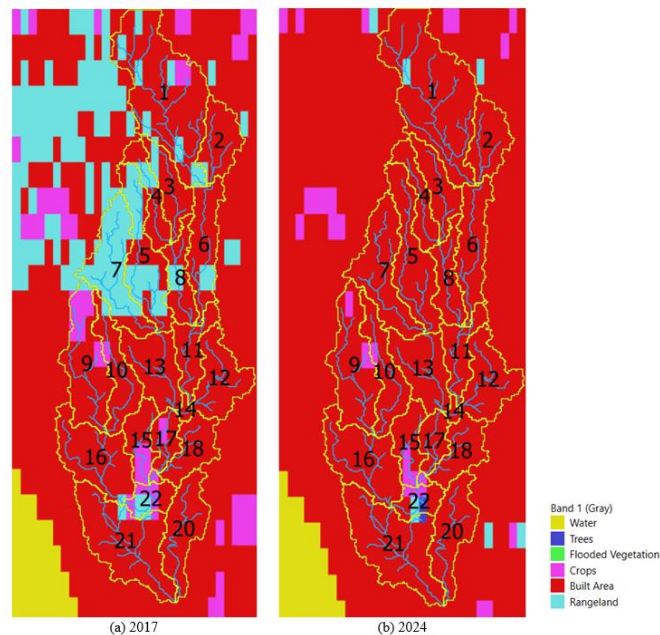


Figure 1. Land Use Change 2017-2024

Aquifer Storage Change : Figure 2 represents aquifer storage (stor) in millimeters (mm), comparing conditions between 2017 and 2024. In 2017, aquifer storage values ranged from 263.40 to 273.31 mm, with high storage zones (blue areas) concentrated in the northern and southern sub-basins (especially Sub-basin 22). These regions coincide with areas previously dominated by trees and crops, which promoted substantial groundwater recharge and sustained aquifer replenishment. By 2024, the spatial extent of these high-storage zones had declined sharply, with most sub-basins exhibiting lower storage values (263.40–265.05 mm) represented in lighter yellow shades. This pattern corresponds strongly with the loss of vegetation and increase in built-up and rangeland areas, as observed in the land use map. Reduced infiltration and higher runoff rates limit aquifer recharge, thereby depleting groundwater reserves. The persistence of moderate to high storage in Sub-basin 22 indicates its resilience as a groundwater reservoir, likely due to favorable hydrogeological characteristics such as permeable alluvial deposits, flat topography, and vegetated lowlands. In contrast, the northern regions, once high in storage, now experience depletion due to anthropogenic land transformation and possibly declining rainfall infiltration.

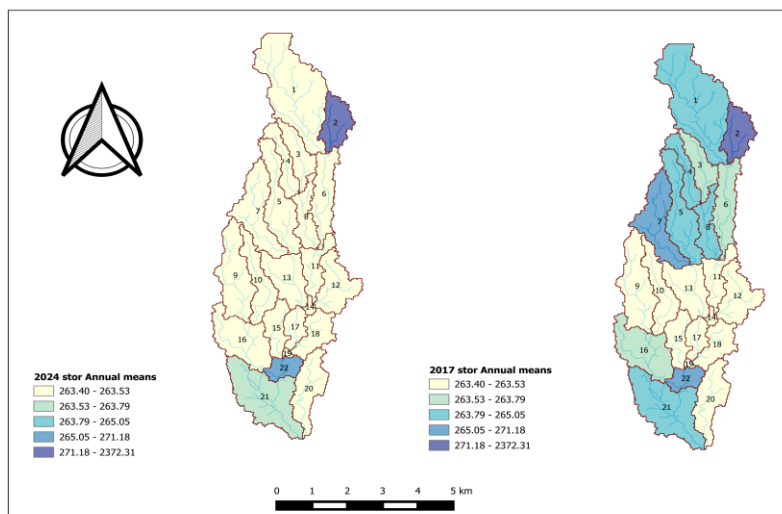


Figure 2. Aquifer Storage Change 2017-2024

Depth From Surface To Aquifer Water Table Change :Figure 3 presents the average annual depth from surface to aquifer water table (dep_wt) in meters, serving as an indicator of groundwater level dynamics. In 2017, the watershed exhibited a relatively shallow water table across central and southern sub-basins (dep_wt 4.46–4.61 m, shown in green), indicating high groundwater availability and strong recharge conditions. These shallow depths are associated with vegetated zones (trees and crops) where infiltration was efficient and percolation sustained aquifer recharge. By 2024, a clear deepening of the water table occurred in most parts of the watershed (dep_wt > 4.61 m, shown in orange to red). This indicates a decline in groundwater levels, which aligns with the observed decrease in aquifer storage and reduction in recharge potential. The deepest water tables now occur in the northern sub-basins, areas that experienced the most extensive land use conversion to impervious cover and loss of vegetation. Meanwhile, Sub-basin 22 again demonstrates relative stability, maintaining shallower water tables due to its consistent recharge potential and minimal land disturbance.

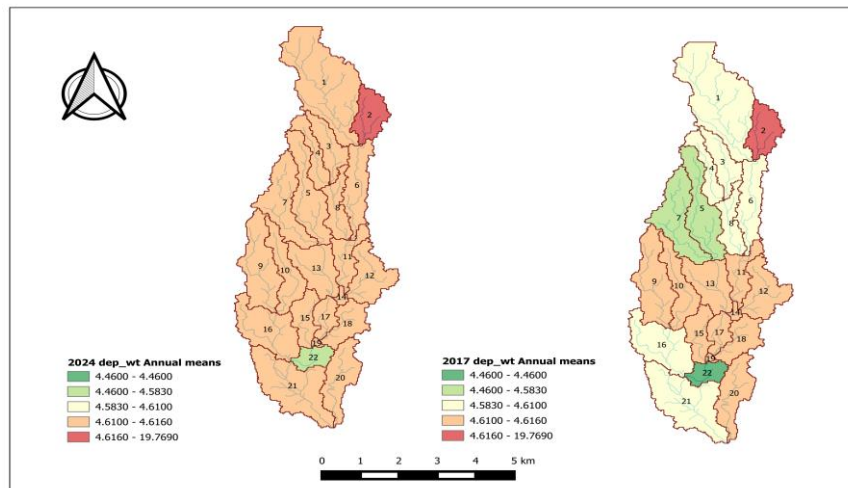


Figure 3. Depth From Surface To Aquifer Water Table Change 2017-2024

Aquifer Recharge Change :The spatial distribution maps of annual groundwater recharge (rchrg) for 2017 and 2024, derived from the SWAT+ model, reveal clear temporal and spatial variations influenced by land use changes and associated hydrological responses within the watershed. The maps employ identical legend ranges divided into five recharge classes: 0.00–0.21 mm (Light Yellow) indicating *very low recharge zones* with minimal infiltration and high surface runoff; 0.21–0.66 mm (Light Green) representing *low recharge areas* with limited infiltration capacity; 0.66–0.95 (Cyan) denoting *moderate recharge zones*; 0.95–3.84 mm (Light Blue) characterizing *high recharge potential*; and 3.84–8.30 mm (Dark Blue) corresponding to *very high recharge areas* where groundwater infiltration is dominant. The spatial distribution of these classes is governed by interactions among land use, soil permeability, slope gradient, rainfall intensity, and vegetation cover, which collectively control the hydrological response and recharge behaviour of the watershed.

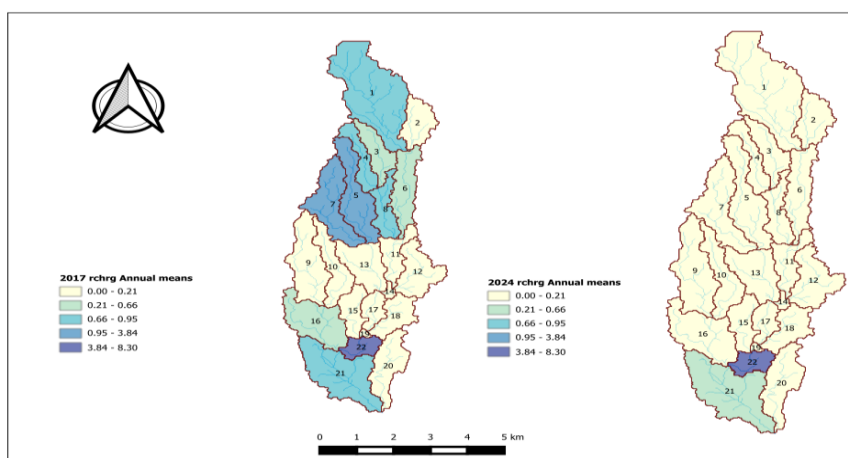


Figure 4. Aquifer Recharge Change 2017-2024

In 2017, the northern and central sub-basins exhibited predominantly high to very high recharge values (0.95–8.30 mm), as represented by light to dark blue tones. These areas were primarily covered by forests, plantations, and agricultural lands, which facilitated higher infiltration rates and groundwater replenishment due to the presence of permeable soils and vegetative cover that enhanced surface water infiltration. The southern region, particularly Sub-basin 22, also demonstrated substantial recharge potential, reflecting its favorable topography, lowland position, and riparian characteristics that promote infiltration and groundwater storage. By 2024, however, a pronounced decline in recharge potential was observed, with large portions of the northern and central watershed shifting into lower recharge classes (0.00–0.66 mm) shown in light yellow to cyan colors. This shift reflects the impacts of land use change—notably, the conversion of forested and agricultural lands into built-up or impervious areas such as settlements and infrastructure. Such changes reduce infiltration capacity, increase surface runoff, and subsequently diminish groundwater recharge. Additionally, soil compaction, deforestation, and altered rainfall regimes may have further contributed to the reduced recharge rates. Despite these widespread declines, Sub-basin 22 retained relatively high recharge potential, suggesting stable hydrogeological conditions characterized by permeable alluvial soils, gentle slopes, and vegetative cover that remain conducive to infiltration. The comparison between 2017 and 2024 reveals that land use change has been a primary driver of declining groundwater recharge, particularly in the upper and middle sections of the basin.

Seepage Out of The Aquifer Change : The top left map, representing the *percentage change in seep* from 2017 to 2024, shows that the color scale indicates the degree of seepage alteration. Areas in red, ranging from –100 to –53%, exhibit a significant decline in seepage, meaning water infiltration or seep flow has drastically reduced—particularly in the middle and southern parts such as sub-basins 13 and 16. Yellow regions (–53 to –0%) represent areas where seepage conditions remain relatively stable or have slightly improved. This suggests that most of the central and southern zones experienced a substantial loss of seepage over the study period.

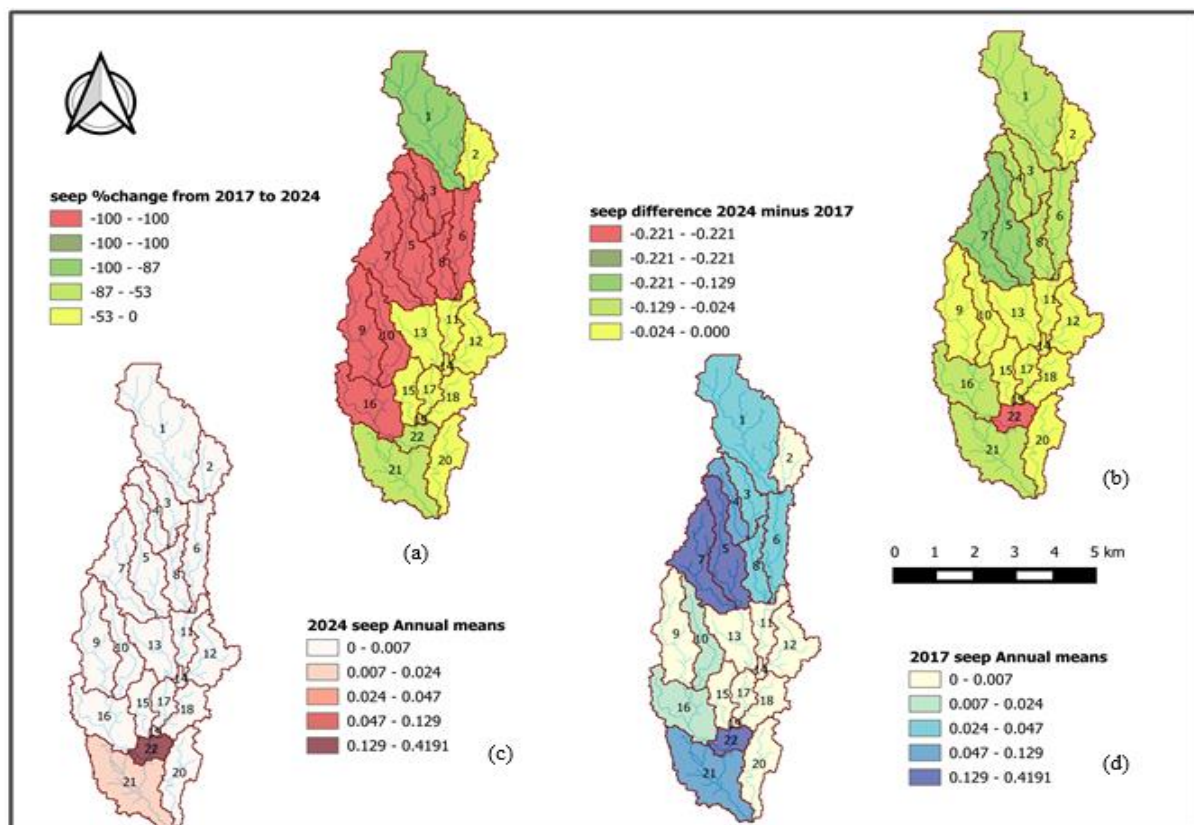


Figure 5. Seepage Out of The Aquifer Change 2017-2024

The top middle map, displaying the *absolute difference in seep* (2024 minus 2017), provides a clearer quantification of this reduction. The difference values range from –0.221 mm to 0 mm, where darker green tones (–0.221 mm to –0.129 mm) indicate a large decrease in seep, and lighter green shades (–0.129 mm to –0.024 mm) show smaller reductions.

Values close to zero (-0.024 mm to 0 mm) imply minimal change. All sub-basins show negative differences, confirming that seepage in 2024 is consistently lower than in 2017, revealing an overall decline in subsurface water movement. The bottom right map presents the *annual mean seep for 2017*. The seep values are categorized into five classes: 0.000 mm -0.007 mm (very low seep), 0.007 mm -0.024 mm (low seep), 0.024 mm -0.047 mm (moderate seep), 0.047 – 0.129 mm (high seep), and 0.129 mm -0.419 mm (very high seep). In 2017, the southern area, particularly sub-basins 13–16, displayed higher seep values (blue tones), suggesting greater infiltration and groundwater recharge potential, while the northern parts exhibited lighter colors, indicating lower seep values. By contrast, the bottom left map, showing the *2024 annual mean seep*, reveals that many previously high-seep zones have shifted to brown or red tones, representing much lower seep values. This indicates a reduction in infiltration or subsurface flow across much of the watershed in 2024. A numerical comparison highlights these changes more explicitly. For instance, sub-basin 13 showed a decline from approximately 0.12 mm to 0.03 mm (-0.09 ; -75%), and sub-basin 16 from 0.10 mm to 0.02 mm (-0.08 ; -80%). Sub-basin 27 exhibited a smaller reduction (-20%), while sub-basin 3 remained stable (0%). These shifts suggest that southern sub-basins are experiencing substantial hydrological stress, possibly due to reduced recharge, land-use changes, or an increase in impervious surfaces that limit infiltration.

IV.

DISCUSSION

Between 2017 and 2024, the watershed underwent a substantial transformation from a predominantly vegetated and agricultural landscape to a more urbanized environment. The expansion of built-up areas and rangeland replaced trees and crop-dominated regions that had previously supported infiltration and groundwater recharge [15]. This land use change disrupted the natural hydrological cycle, leading to increased surface runoff and a decline in infiltration rates [16], [17], [18]. Consequently, less water percolated into the aquifer, resulting in decreased storage and recharge capacity. Such transformations are characteristic of rapidly developing catchments worldwide, where urbanization reduces natural recharge zones and alters subsurface flow regimes, ultimately diminishing the sustainability of groundwater systems. Aquifer storage exhibited a marked decline across the watershed, with the most significant reductions occurring in sub-basins that experienced extensive land conversion [19], [20]. In 2017, aquifer storage values ranged between 263.40 and 273.31 mm, reflecting healthy infiltration conditions supported by vegetation cover. By 2024, the storage range had narrowed to 263.40 – 265.05 mm, signifying a clear depletion of groundwater reserves. This reduction can be attributed to a combination of reduced infiltration, elevated surface runoff, and potentially increased groundwater extraction for domestic and agricultural uses [21], [22]. However, Sub-basin 22 retained higher storage values, suggesting localized hydrogeological resilience attributed to favorable soil permeability, low-lying alluvial formations, and consistent vegetative cover that supported continued groundwater recharge.

The depth from the surface to the aquifer water table (dep_wt) deepened significantly between 2017 and 2024, reflecting a general decline in groundwater levels throughout the watershed. In 2017, shallow water tables (4.46 – 4.61 m) were characteristic of vegetated and agricultural zones that facilitated recharge. By 2024, these values exceeded 4.61 m in many sub-basins, especially in northern and central regions that underwent extensive urbanization and vegetation loss. This deepening trend signals reduced groundwater availability and the potential emergence of water stress conditions, which could impact both ecosystems and human water use. Sub-basin 22, however, maintained a relatively stable groundwater depth, reinforcing its role as a hydrologically resilient area critical for sustaining regional groundwater resources. Groundwater recharge (rchrq) showed a significant spatial and temporal decline over the same period. In 2017, recharge values between 0.95 and 8.30 mm were observed predominantly in the northern and central sub-basins, corresponding to forested and agricultural lands with high infiltration potential. By 2024, most of these areas had shifted to lower recharge classes (0.00 – 0.66 mm) as a result of increased impervious surfaces associated with urban expansion. The reduction in recharge underscores the strong relationship between land cover and infiltration capacity—where deforestation, soil compaction, and reduced permeability hinder groundwater replenishment. Nevertheless, Sub-basin 22 continued to exhibit relatively high recharge rates, indicating a more balanced land–hydrology interaction and emphasizing the importance of its conservation for watershed sustainability.

Seepage from the aquifer also declined drastically between 2017 and 2024, as revealed by spatial analysis showing reductions of 50 – 100% in several sub-basins, particularly in the southern portions (Sub-basins 13–16). These areas, previously characterized by higher seepage and active groundwater discharge, now exhibit reduced subsurface flow connectivity. This decrease indicates limited replenishment of shallow aquifers and declining hydraulic connectivity between groundwater and surface systems. The consistent negative seepage differences

Across all sub-basins reflect a watershed-wide decline in subsurface hydrological activity, which can reduce baseflow contributions to streams and increase the likelihood of dry-season water shortages and ecosystem degradation. When analyzed collectively, the spatial patterns across all hydrological variables—land use, aquifer storage, groundwater depth, recharge, and seepage—demonstrate a coherent response to intensified anthropogenic pressures. The expansion of impervious surfaces and land degradation has disturbed the natural equilibrium between infiltration and runoff, leading to a systemic reduction in groundwater availability [23], [24]. Amid these widespread declines, Sub-basin 22 emerges as a critical groundwater conservation area, maintaining relative hydrological stability due to favorable geological and topographical characteristics. Safeguarding such zones is vital for maintaining aquifer function under ongoing land use changes and climate variability.

These findings highlight the urgent need for integrated watershed management and land use planning aimed at mitigating further groundwater depletion. Restoration strategies such as reforestation, creation of vegetative buffer zones, rainwater harvesting, and control of built-up area expansion are essential to enhance infiltration and recharge. Additionally, continuous hydrological monitoring using modelling tools like SWAT+ is recommended to predict the impacts of different land management scenarios on groundwater sustainability. Strengthening institutional coordination and adopting nature-based solutions can further ensure that development within the watershed aligns with long-term water resource conservation and climate resilience objectives.

V. CONCLUSION

The results of the SWAT+ simulation from 2017 to 2024 clearly demonstrate that rapid land use change has significantly altered the hydrological dynamics of the watershed. The conversion of vegetated and agricultural areas into built-up and rangeland zones has disrupted the natural balance between infiltration and runoff, leading to widespread declines in groundwater-related parameters. Aquifer storage has decreased considerably due to reduced infiltration and increased surface runoff, while groundwater levels have deepened, indicating a decline in subsurface water availability. Similarly, both groundwater recharge and seepage have experienced substantial reductions, particularly in sub-basins heavily affected by urban expansion and vegetation loss. These hydrological changes collectively point to a systemic degradation of the watershed's ability to retain and replenish groundwater resources. However, Sub-basin 22 consistently demonstrates relative resilience across all indicators, maintaining higher aquifer storage, stable groundwater depths, and stronger recharge capacity. This resilience can be attributed to its favorable hydrogeological conditions—such as permeable alluvial soils, low-lying topography, and persistent vegetative cover—which facilitate effective infiltration and groundwater recharge.

The result emphasizes the critical need for integrated watershed and land use management strategies to mitigate ongoing groundwater depletion. Sustainable practices such as reforestation, soil conservation, infiltration zone restoration, and rainwater harvesting should be prioritized to enhance recharge and restore hydrological balance. Furthermore, the incorporation of hydrological models like SWAT+ in regular watershed monitoring and policy formulation will be essential to evaluate the long-term effects of land use planning and climate variability. Protecting resilient zones such as Sub-basin 22 and implementing nature-based solutions across the watershed are key steps toward ensuring sustainable groundwater management and long-term water security.

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