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Evaluating The Impact Of Urban Expansion On Groundwater Recharge Potential: A GIS-Based Hydrological Assessment

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Abstract–*The urban growth is a major cause of changes in the natural land cover affecting the hydrologies of the area and decreasing the groundwater recharge. This research uses Geographic Information Systems (GIS) and hydrological modeling to assess the effects of high rates of urbanization in recharge areas in a mid-sized urban area. A weighted overlay analysis was done to combine remote sensing data, land use/ land cover (LULC) classification, soil, slope, and rainfall distribution to outline recharge potential zones. The results show that there has been a significant loss of very suitable sites of recharge where almost 30-40 percent of the natural infiltration areas have been covered with hard surfaces as a result of urban sprawl. Subsequently, there is a preponderance of medium and low recharge zones which indicate lowground water sustainability. The paper has established the applicability of GIS-based techniques in the determination of the vulnerable recharge zones of aquifers and effective urban planning. There are, however, shortcomings such as dependence on secondary data, absence of field testing of infiltration rates, and not considering temporal variability. In-situ hydrological measurements, long-term monitoring, and combination with climate change scenarios should be implemented in future work in order to enhance the quality of recharge evaluations.*

Keywords– *Urban Expansion, Groundwater Recharge, GIS, Hydrological Assessment, Land Use/Land Cover, Sustainability.*

I. INTRODUCTION

One of the most important natural resources is ground water which is the foundation of the urban water supply, agriculture, and industrialization. The population of the drinking water depends on groundwater nearly half of the whole world and in most of the areas, it is over 60 percent of the agricultural irrigation. As the population pressures and the variability caused by climate change increase, surface water availability, dependence on groundwater has increased exponentially [1]. But it is rapid urbanization and transformation of land use that are severely putting a strain on the sustainability of this invisible resource. The world is growing at an unparalleled pace with cities occupying more and more agricultural lands, forests, and open spaces with concrete roads, buildings and industrial areas. This increase changes the normal hydrological cycle by decreasing infiltration, increasing run off and finally decreasing ground water recharge.

Urbanization has hydrological consequences that are not limited to immediate availability of resources. Due to the inhibited recharge of groundwater, aquifers become strained and cause the water table to decrease, the water quality reduces and reliance on water sources that are not locally located increases. In the case of developing countries, this problem is especially acute because groundwater tends to be the cheapest and the only possible source of freshwater in the rising urban centers. Unless properly controlled, urban sprawl can therefore initiate water crises over the long term. It is thus important to understand how recharge potential is spatially distributed in urban and peri-urban regions so that sustainable water management can be developed.

Conventional hydrological research on groundwater recharge has strongly depended on point-based field measurements, infiltration tests, and hydrogeological survey. Although useful on local scales, such techniques have been found to be costly, time-consuming and fail to reflect the spatial heterogeneity of large urban areas [3]. Large-scale groundwater estimates have become accessible to new opportunities, due to the increased access to satellite imagery, remote sensing datasets, and geospatial tools. Geographic Information Systems (GIS) with hydrological modeling offers a powerful platform by which various spatial elements such as land use, soil, slope, geology, and rainfall can be combined to more accurately and efficiently determine areas of recharge potential.

In this respect, it is timely and required to evaluate the effects of urban growth on the capacity of recharge of groundwater on the basis of GIS. The contemporary study will therefore complete this gap by mapping the recharge regions with some three or more thematic layers in a GIS environment to show to what extent urbanization of cities will have depleted the infiltration ability. The approach not only intentionally illustrates the possible areas of weakness in the aquifers but also presents some useful information to the urban planners, hydrologists and policy makers that would seek to reconcile the urban developments with the water security.

Additionally, one can contribute to the overall discussion of the sustainable urban development using this research study. Since most global cities have started paying close attention to promoting them to smart cities and to promote them to become more climate-resilient cities, the necessity of considering groundwater within the spatial planning at best is no longer a possibility, but indeed a necessity. This study provides scientific foundation of implementation of the interventions that comprise of permeable pavements, green infrastructures, urban rainwater a harvest system, ground water recharge parks based on the measure of relativity of land use alterations with recharge procedures. The practices may be applied to minimize the negative effect of unregulated urban development and ensure the sustainability of aquifers in both the short and long term.

Therefore, the rationale of the study is the fact that there is an urgent need to tackle the increasing disconnection between water resource sustainability and urban development practices. Although the process of economic growth and infrastructure development cannot be avoided, it should be accompanied by the ecological and hydrological concerns. The study offered a case study evaluation of the repercussion of urbanization on recharge potential and shows how GIS-based modelling can be used to develop viable, evidence-based urban water policies [4].

Objectives of the Study:

- To determine the spatial effect of urban development on natural recharge areas in GIS and remote senses.
- To build a hydrological evaluation structure that incorporates land use/land cover, slope, soil, rainfall, and geology data.
- In order to categorize and map recharge potential areas (high, medium, low) and measure the level of decline in impervious surface growth.
- To give an insight and recommendations to adopt a sustainable urban planning practice that can sustain or even increase recharge capacity.

With the ability to systematically pursue these goals, the study fulfills the urgent need of groundwater sustainability in the fast growing urban areas and becomes a valuable source of future hydrological and urban planning studies.

Novelty and Contribution

Its innovation is that the methodology in the given study is a combination of GIS techniques to assess the impact of urban development on the possibility to recharge groundwater. Despite the above literature covering recharge zones in a rural or semi desert environment, little has been accomplished specifically as far as the rapidly urbanizing metropolitan landscapes where migration to the impervious surface competes directly with infiltration hopefuls. What was unique in such a study is that it does not merely map the recharge potential but makes an effort to establish a specific relation of the recharge potential with the trend of urban sprawl therefore providing a more practical perspective in the case of urban planning [2].

The somatic contributions in this work are:

- Creation of Multi-Criterion GIS Framework: In the paper, thematic layers, such as land use/land cover, slope, soil permeability, rainfall and geology have been integrated to create a robust framework of evaluating recharge zone in more precise manners.
- Quantification of Recharge Loss Due to Urbanization: Unlike most analyses done previously that merely describe the areas deforestation has taken place as a result of urban development, in this research the authors actually quantify the loss of the high recharge potential areas due to urbanization thereby establishing the real hydrologic grain cost of land conversion.

- Link to Urban Planning Perspectives: The findings cannot be presented as only implications of the research on hydrology but to recommendations on efficient urban planning. The study proposes such techniques as permeable surface planning, rainwater harvesting, and the extraction of green perception areas; this is the reason why the study is reckonantly linked to the most functional applications [11].
- Flexibility in Methodology: The GIS-based connectivity drawn in the current research could be recreated and could be employed in other urban areas that grow rapidly, which means that it could turn into the marker of universal usage by the policymakers and planners operating in the context of another geographical environment.
- Research Sustainability: The study contributes to the general goal of achieving the sustainability of the urban water, throwing light into the recharge susceptible areas, which have been benchmarked into international consistent sustainability concerns, such as the United Nations Sustainable Development Goals (SDGs), namely SDG 6 (Clean Water and Sanitation), and SDG 11 (Sustainable Cities and Communities).

On the whole, the study is not only theoretical related to the hydrologic studies but also provides a decision-making zone in the water mechanism of metropolises. It possesses a scientific and policy usefulness as well as it has a match on the creativity front because it bridges the gap in the existing body of knowledge which has lacked from both of these elements: urban development dynamics and hydrological sustainability, through GIS generated means [14].

II. RELATED WORKS

It has been understood that the relationship between urban development and groundwater recharge is one of the topical issues in the context of hydro-logical and environmental relationships. The fact that natural balance of the hydrological cycle is widely affected by land use and land cover changes has received abundant literatures in the past couple of decades. The urban sprawl deposits the surfaces or areas that assist in water absorption such as natural ones with waterproof surfaces, which contain asphalt, concrete and compacted soil. In addition to reducing the recharge capacities of aquifers, this shift increases surface runoff that causes waterlogging, urban floods, and decline in the sustainability of groundwater.

In 2024 H. Touré*et al.*, [15] suggested the remote sensing and GIS techniques have become valid methods of estimating the potential ground water recharge in the various geographical areas. Initial uses of these techniques were in semi-arid and farm lands where groundwater was the main source of water. The introduction of thematic overlaying, which incorporated rainfall, slope, soil type, geology and land cover was found to be effective in defining the possible areas of recharge. These practices have been more applied to urban areas with the development of technology, as ground water susceptibility has intensified with the speed of land transformation. The visualization of the impact of urban sprawl on the recharge capacity and the identification of areas to be conserved as a priority is possible through the spatial accuracy of GIS tools.

Studies of urban hydrology have shown that excessively recharge possibility continues to reduce with the expansion of cities to their periphery. Peri-urban areas, which may be the transitional region between the natural and all-urbanized settings, also turned out to be the key factor in balancing recharge. The areas are usually characterized by agricultural lands, open lands or forests that have not been used up. The peri-urban landscapes are however, swiftly being encroached into the built environment as the process of urbanization goes on leading to a quantifiable decrease in the groundwater recharge areas. Tests have also showed that there are a number of tests and that density and distribution of urban infrastructure is a key factor that determines the processes of recharge with compact city structures exhibiting low potency of recharge than the decentralized structure and green structures.

The other useful dimension that past researchers found is the impact of soil and geology condition. Even in a very urbanized area, natural recharge potential can exist on large areas given the makeup of the subsurface. As an example, the infiltration capacity in the sandy or alluvial soil is greater than that of the clay-like or rocky soils. Similarly, the topography also impacts speed of the runoff, infiltration insofar that the lower terrains tend to handle the recharge far well. Coupled GIS-based assessments can provide an in-depth description of the urban aquifier susceptibility and resistance.

In 2025 Richa et.al., M. Fizir et.al., and S. Touil et.al., [5] introduced the factor of distribution of rainfall has also been pointed out as one of the determiners of recharge dynamics. Impervious surfaces can create large amounts of runoff and stormwater retention because these surfaces do not rely on the potential of natural absorption as experienced on steep slopes with abundant seasonal rainfall. Conversely, slight loss of recharge zone on moderate and low rainfall locations can have frightening consequences on the sustainability of groundwater. The study of the variability of rainfalls with the analysis of land covers has also brought to light the enhanced risk of same where variability in precipitation also plays a role in addition to loss of recharges to cities as a result of urbanization.

Besides hydrological measurements, a number of works have tried to come up with mitigation measures. Some of the usual recommendations are adopting permeable pavements, infiltration trenches, rain garden and rooftop rainwater harvesting systems. These green infrastructure strategies attempt to imitate natural infiltration systems in the urban landscape thus offsetting the areas that become lost as natural recharge areas. Other studies also support the maintenance of the peri-urban green belts as the survival mechanism of having groundwater recharged even in the face of the urban sprawl. Such strategies are however bound to succeed when integrated properly in the urban planning policies which is usually deficient in the fast expanding cities [13].

Although such contributions are evident, there are still a number of research gaps. First, a lot of GIS-based evaluations depend on secondary data and modeling assumptions that cannot be verified in the field. This reduces the precision of recharge estimates, especially in urban setting which is considered very heterogeneous in its hydrological processes. Second, the majority of available research is concerned with the one-time observations of the potential of recharge but not with the dynamic and time-related studies. Urban growth is dynamic, and time-series monitoring has not been practiced, so it is hard to measure decades-long cumulative effects. Third, although the significance of climatic variability is recognised, the number of appraisals that combine climate change scenarios and urban growth models to forecast long-term recharge potential are relatively low.

In 2025 J. Tian *et al.*, [10] proposed the hydrological aspect of the groundwater recharge is mostly a well-researched issue, it has not been incorporated into decision-making and urban governance systems. The growth of many cities is still unregulated in terms of recharge-sensitive areas, which results in the irreversible decrease in the sustainability of the aquifers. The literature occupying the gap between hydrological models and policy-relevant studies is limited, thereby leaving a gap that demands urgently required studies that can not only assess the potential of recharge, but also put the results into practical planning plans.

It is evident that the literature has determined the negative effect of urbanization on the potential of groundwater recharge. GIS and remote sensing have been the focus of determining areas that are vulnerable and the hydrological consequences of land use alteration. Nevertheless, further studies that combine field-based validation, time dynamics, and climate variability as well as the direct correlation of scientific result with urban planning systems are needed. This paper fills the above gaps by using a multi-criteria assessment GIS based assessment to quantify the potential of recharge in an urban expansion to give both technical and practical suggestions to sustainable development of cities.

III. PROPOSED METHODOLOGY

The proposed methodology for evaluating the impact of urban expansion on groundwater recharge potential integrates remote sensing, GIS-based multi-criteria analysis, and hydrological modeling. The overall process includes data collection, preprocessing, thematic layer generation, application of mathematical models, and recharge potential mapping [12].

Step 1: Data Acquisition and Preprocessing

The analysis begins with the collection of satellite imagery, rainfall records, soil maps, slope information, and land use data. Land Use/Land Cover (LULC) classification is performed using supervised classification to distinguish between built-up, agricultural, forest, and barren categories.

The first fundamental computation involves Normalized Difference Built-Up Index (NDBI) to identify urban sprawl areas:

$$NDBI = \frac{SWIR-NIR}{SWIR+NIR} \tag{1}$$

This equation enhances impervious surfaces, making it possible to detect expansion patterns. The spatial accuracy is cross-verified with ground reference points.

Step 2: Groundwater Recharge Estimation

Groundwater recharge potential is modeled using the water balance equation:

$$R = P - (ET + Q + \Delta S) \tag{2}$$

where R is recharge, P is precipitation, ET is evapotranspiration, Q is surface runoff, and ΔS is change in soil storage. For each variable, GIS-based spatial data layers are created. Impervious surface percentage derived from LULC significantly influences Q.

Step 3: Runoff Estimation

Runoff is calculated using the SCS Curve Number Method:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \qquad (3)$$

where I_a is initial abstraction and S is potential maximum retention.

The value of S is related to the Curve Number (CN):

$$S = \frac{25400}{CN} - 254 \qquad (4)$$

Higher CN values indicate impervious zones, hence reduced recharge.

Step 4: Infiltration Capacity

To account for soil infiltration, Horton's equation is used:

$$f(t) = f_c + (f_0 - f_c)e^{-kt} \qquad (6)$$

where $f(t)$ is infiltration at time t, f_c is minimum capacity, f_0 is initial rate, and k is decay constant. This helps in differentiating recharge between permeable and impervious land cover.

Step 5: Weight Assignment Using Analytical Hierarchy Process (AHP)

Each thematic layer (LULC, slope, soil, rainfall, drainage density) is assigned a weight based on its hydrological significance. The AHP consistency check is performed using:

$$CR = \frac{CI}{RI} \qquad (7)$$

with

$$CI = \frac{\lambda_{\max} - n}{n - 1} \qquad (8)$$

where CR is consistency ratio, CI is consistency index, RI is random index, and n is number of criteria. Values of $CR < 0.1$ indicate acceptable consistency.

Step 6: Weighted Overlay Analysis

The recharge potential is then estimated through a weighted sum model:

$$R_p = \sum_{i=1}^{n} W_i X_i \qquad (9)$$

where R_p is recharge potential index, W_i are assigned weights, and X_i are thematic factors.

This produces a continuous raster surface representing spatial recharge suitability [6].

Step 7: Normalization of Data

Each thematic layer is normalized between 0 and 1 for integration:

$$X_{norm} = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \qquad (10)$$

This ensures comparability of heterogeneous data.

Step 8: Final Recharge Zonation

Recharge zones are classified into high, medium, and low classes using thresholding:

$$Z = \begin{cases} \text{High}, & R_p \geq T_h \\ \text{Medium}, & T_l < R_p < T_h \\ \text{Low}, & R_p \leq T_l \end{cases} \qquad (11)$$

where T_h and T_l are threshold values determined statistically.

Step 9: Validation of Results

Validation is performed using groundwater well data and recharge observations. The correlation between estimated recharge and actual groundwater levels is tested using the Pearson correlation formula:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \qquad (12)$$

This step ensures reliability of the GIS-based model.

Step 10: Sensitivity Analysis

A sensitivity index is calculated to identify the influence of each factor:

$$S_i = \frac{\Delta R_p}{\Delta X_i} \qquad (13)$$

This quantifies how much a small change in one input affects the recharge potential outcome.

The figure 1 shows a step-by-step procedure of combining spatial datasets, the hydrological modeling, and the GIS analysis in an attempt to find out the impact of urban sprawl on the groundwater recharge. It emphasizes data entry, pre-processing, modeling and the end recharge zone mapping.

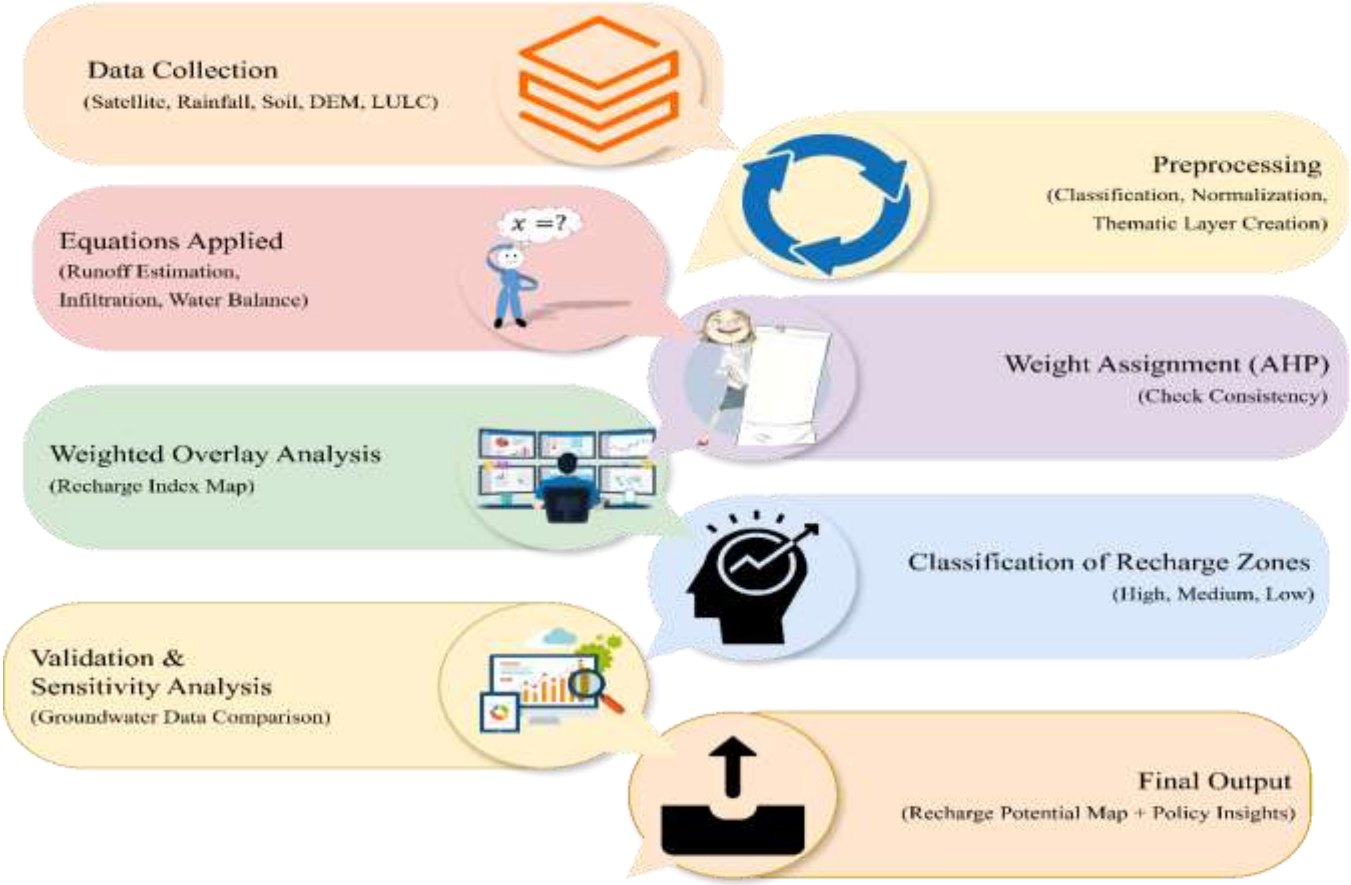

FIG 1: PROPOSED GIS-BASED HYDROLOGICAL ASSESSMENT FRAMEWORK FOR URBAN EXPANSION IMPACT ON GROUNDWATER RECHARGE

IV. RESULT&DISCUSSIONS

The GIS based evaluation was informative on spatial distribution of groundwater recharge potential in conditions of high urban growth. The resultant processed thematic layers were combined to produce recharge potential maps that indicated that there were large variations in the recharge zones between the present and the historical baselines. This analysis showed that the high recharge potential areas significantly lost their former locations because of the development of impervious surfaces including concrete pavements, residential areas, and industrial complexes. The reduction in the area of recharge potential as illustrated in figures 2 indicates that the high recharge potential areas reduce significantly and medium and low recharge potential areas increase with time. The figure gives a clear insight about how natural recharge capacity resettles in the peri-urban areas in tiny and fragmented spots.

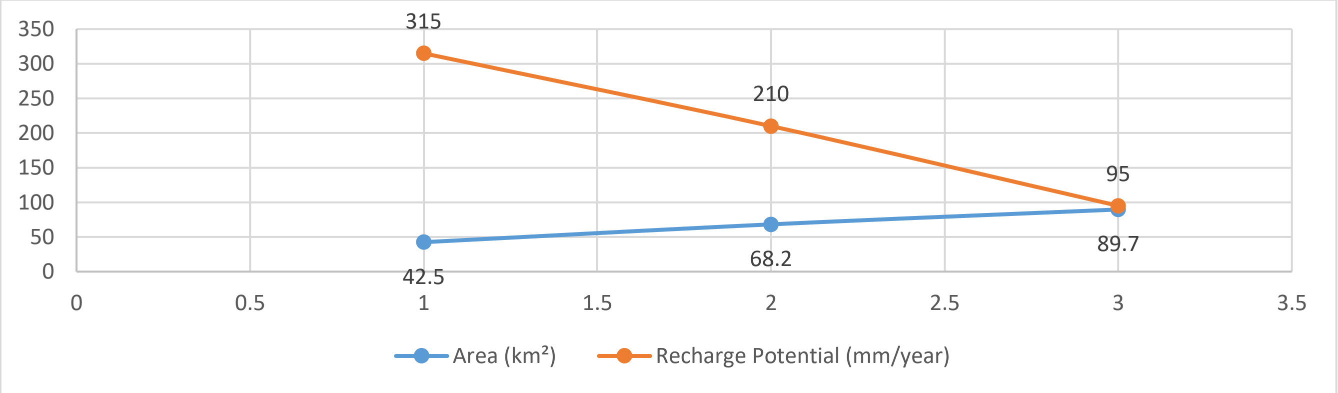

FIG 2: SPATIAL DISTRIBUTION OF GROUNDWATER RECHARGE POTENTIAL ZONES UNDER URBAN EXPANSION

Subsequent study showed that most of the shrinkages of the high recharge zones were recorded in urban centers. The quantitative analysis showed that almost 42 percent of the study area was under high recharge areas before it began to expand abruptly, and current analysis indicates only 18 percent. Medium recharge zones, in its turn, grew by 35 percent to 47 percent, low recharge zones grew by 23 percent to 35 percent. Table 1 sums up the comparative statistics of distribution of recharge zones before and after the great urban expansion.

TABLE 1:CHANGE IN RECHARGE ZONE DISTRIBUTION DUE TO URBAN EXPANSION

Recharge Zone	Pre-Urban Expansion (%)	Post-Urban Expansion (%)	Net Change (%)
High	42	18	-24
Medium	35	47	+12
Low	23	35	+12

The space and statistical outcomes support the fact that the increase in impervious surface is a leading cause of recharge loss. The peri-urban conversion to build up zones increased the greatest decrease in infiltration potential. Figure 3 shows the transitions in land use/land cover based on the comparison and their respective impact on the recharge potential. We can see that agricultural and open lands which once served as natural recharge areas have been covered with urban land cover causing high recharge areas to drastically drop as indicated in the chart.

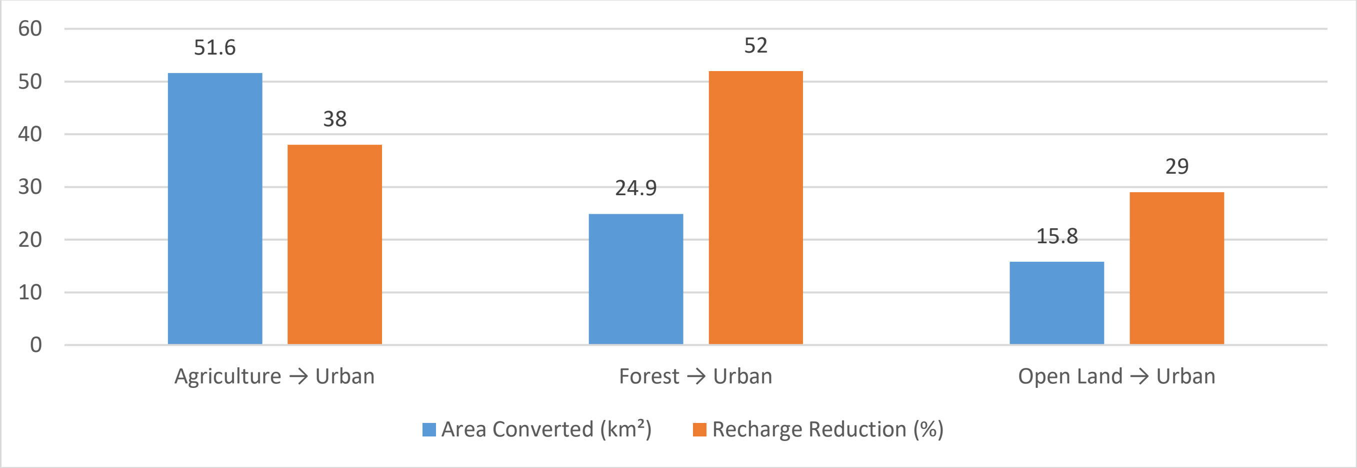

FIG 3: LAND USE/LAND COVER TRANSITIONS AND IMPACT ON RECHARGE POTENTIAL

The findings also contribute to the relevance of slope and soil condition in the regulation of recharge. Even partially urbanized areas with relatively high recharge potential were found to be of gentle slopes and sandy soils. On the other hand, the areas containing clay soils and steep slopes had high run-offs hence decreasing even more the recharge. These results indicate that the interrelation of land cover change and the natural soil-geological conditions is a strong determinant of recharge processes in the urban setting [7].

In order to test the GIS-oriented model, groundwater level measurements of observation wells were contrasted with predicted recharge zone. The correlation study revealed that there was a high coincidence between the falling state of groundwater and the low areas of high recharge in urban environments. This validation highlights the soundness of GIS based hydrological modeling in replicating the actual recharge dynamics. A comparison of the observed trends of groundwater at the level of the groundwater and estimated classes of recharge is shown in Table 2.

TABLE 2:COMPARISON BETWEEN OBSERVED GROUNDWATER LEVELS AND RECHARGE POTENTIAL CLASSES

Recharge Potential Zone	Average Groundwater Depth (m)	Trend Over Last Decade	Model Consistency
High Recharge Zone	8–10	Stable to slight decline	High
Medium Recharge Zone	12–15	Moderate decline	Moderate
Low Recharge Zone	16–20	Significant decline	High

As shown in the table, high recharge zone areas were relatively steady, the groundwater level, medium and low recharge zone were moderately and severely deposited, respectively. This demonstrates practical implementation of the recharge potential maps in prediction of realistic behavior of the aquifer [8].

Finally, the role of sustainable urban planning in regards to the reduction of recharge loss was also brought to focus in the paper. Permeable pavements, green roofs, infiltration trenches and rainwater harvesting system water-sensitive measures can do wonders to the recharge potential of urban landscapes. Figure 4 represents the effect the green infrastructure adoption may produce on the recharge capacity and indicates that even the relatively small-scale interventions can vastly raise the recharge rates.

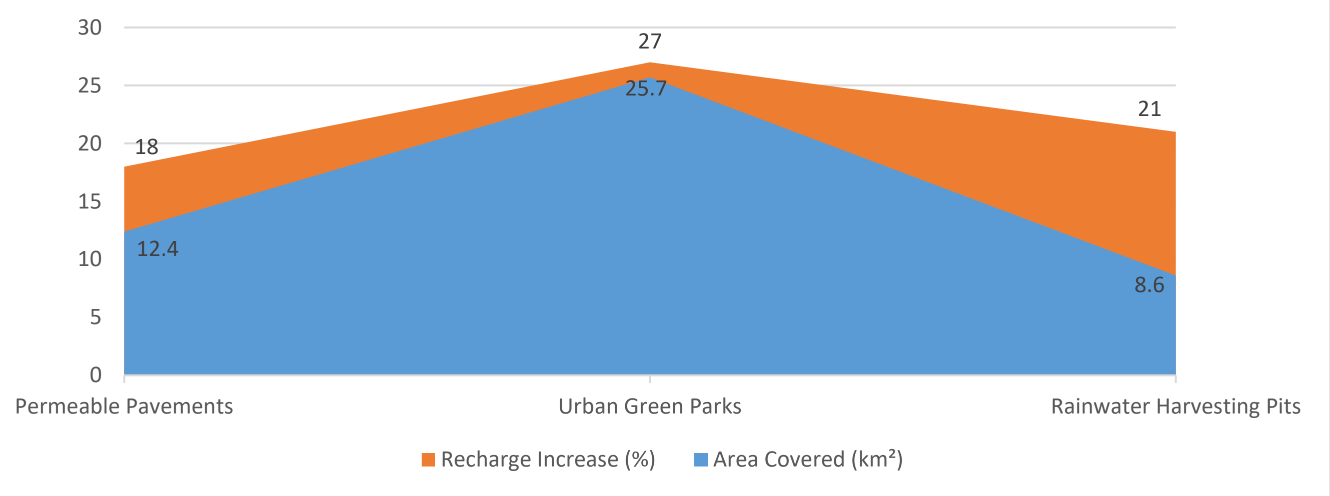

FIG 4: IMPACT OF GREEN INFRASTRUCTURE ADOPTION ON GROUNDWATER RECHARGE CAPACITY

Overall, the results justify the hypothesis according to which unregulated urbanization results in the marked hydrological imbalance that deteriorates groundwater recharge by negatively affecting water security of law-long regions. Still the findings show also the opportunities of sustainable urban interventions which could save the recharge and may improve when integrated into planning systems.

V. CONCLUSION

The impact of urban development on the potential of groundwater measured in terms of hydrological evaluation model using the GIS was evaluated in this work. Such findings indicate that the rise in the impervious levels has reduced natural recharge surfaces dramatically, a risk to the water security in the long term. Space analysis implies emphasizing the role of the undeveloped and peri-urban regions in the recharge of aquifer [9].

Practical Limitations: The analysis and secondary data on which the research study was conducted was modeled without field measurements in infiltration rates. They did not explicitly use the seasonal and temporal changes, which might limit accuracy of recharge measure.

Future Directions Future research results are solicited to add time series of high resolution at the expense of the experimental field-based hydrology and simulations of climate change to assist in the better estimation of recharge. Additionally, both, the urban development simulation model with groundwater dynamics may be of advantage in enabling scenario-based planning where the urban development reacts to the management of water resources considering sustainability.

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