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Evaluating Impact of Sustainable Urbanism Practices: A Simulation Approach

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***Abstract*—** A very effective traffic management strategy in metropolitan cities is the construction of flyovers that allow for convenient distribution of traffic while maintaining emission control. Observing the current scenario of depleting freshwater resources, the project aims towards a sustainable urbanism approach involving the distribution of collected rainwater from flyovers to the underground water table utilizing the preinstalled standard drainage systems. The study is carried out in the metropolitan region of Hyderabad, Telangana, India using a groundwater simulation software called MODFLOW to simulate factors like rainwater absorption, evapotranspiration, runoff and hydraulic head. The sole focus of this simulation is to assess the impact of such a practice in replenishing the underground water table.

***Keywords*— Sustainable Urbanism, Rainwater Harvesting, Flyovers, Environmental Impact, Infrastructure Development**

I. INTRODUCTION

Creative approaches are becoming more and more important as large cities struggle with rising water demands and depleting groundwater supplies. The use of flyovers as catchment sites for rainwater gathering is one possible strategy to alleviate these issues. An exceptional chance to incorporate sustainable water management techniques into the urban infrastructure is provided by flyovers, which are elevated roads intended to reduce traffic and enhance urban mobility.

Designing flyovers to collect and direct rainfall that falls on their surfaces—such as the road, embankments, and supporting pillars—is the idea behind rainwater harvesting. Cities may efficiently collect, store, and use rainwater that would otherwise be lost to runoff by installing a rainwater harvesting system on flyovers. This approach not only helps in augmenting local water supplies but also contributes to the reduction of urban flooding and the management of stormwater.

Flyover designs that incorporate rainwater harvesting systems are in line with the more general objectives of resilience and sustainable urban development. It offers a workable and creative way to increase water availability, lessen the negative effects of development on groundwater supplies, and boost general water management in urban areas. Utilizing existing infrastructure, such as flyovers, for rainwater collection is a progressive approach to tackling the intricate problems of urban water conservation as cities continue to grow and change.

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II. LITERATURE SURVEY

The effects of rainwater harvesting Systems and groundwater estimates have been the subject of numerous studies conducted worldwide. Mohammed-Aslam et al. (2010) used geophysics and remote sensing to assess the potential for underground water in a hard-rock reservoir. Israel et al. (2006) used isotopic and GIS approaches to evaluate groundwater resources in the Piedmont region of the Himalayas, India. Vervoort and Glendenning (2011) investigated the hydrological effects of rainwater harvesting (in Rajasthan, India's Arvari River. Utilizing a conceptual water equilibrium model, this work has investigated the implications of RWH at the watershed scale. According to the modeling results, RWH improves groundwater recharge and irrigation agriculture's sustainability while reducing the flow of streams downstream. Matthew and William (2010) conducted a study at three rainwater reservoirs in North Carolina to examine the effectiveness of rainwater harvesting systems within the southeast region of the US. To simulate the operation of the system, a computational simulation was created, and simulations for bigger reservoirs and 2081 barrels for rainwater were carried out. The monitoring study's findings revealed that the rainwater collecting systems were not being used to their full potential, which was thought to be caused by inaccurate water usage estimates and a negative public impression of the collected rainwater. Simulation data showed that a rainstorm barrel flooded during the majority of rainfall occurrences and was often exhausted when used to satisfy household irrigation needs. The rainwater collection system for Zhoushan, China's residential water supply was examined by Yong-chao Zhou et al. (2010). To examine the effectiveness of the Domestic Rainwater Harvesting System (DRHS) with varying D/(AR) (water demand/average annual collected runoff) and S/(AR) (storage capacity/average annual collected runoff) ratios, they created a computer model. The model simulation was used to examine the DRHS's performance.

III. PROBLEM STATEMENT

As stated in the Central Ground Water Body (CGWB) Telangana Yearbook. Over the last ten years, the water's surface table level in the state of Telangana has significantly decreased.

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Fig.6.2

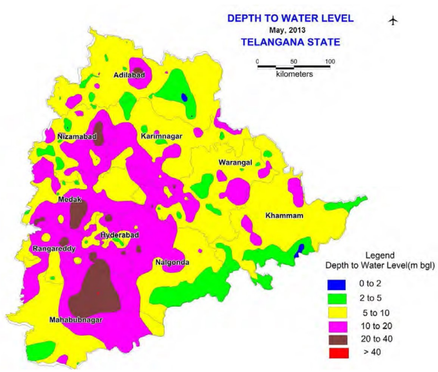

Fig 1. Depth of water level - TS 2013

As underground water from other parts of the state is moved to metropolitan areas to suit the growing demands in towns and cities, urbanism is the primary cause of this change. The underground water recharge-discharge cycle is noticeably out of balance as a result of overproduction of groundwater in metropolitan areas. Water levels drop in areas where groundwater extraction exceeds natural recharge, drying out wells and lowering the amount of water available

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for drinking and farming. This has downstream effects on regions that depend on groundwater flow from the near locations where groundwater is removed, in addition to the immediate areas themselves.

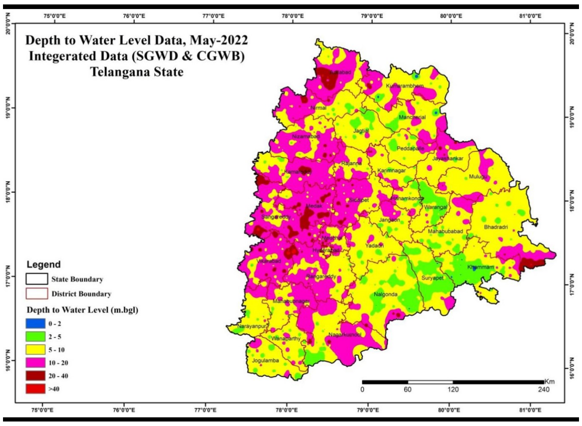

Fig 2. Depth of water level - TS 2022

Because deeper wells and more sophisticated technology are needed to access the dwindling water supplies, the socioeconomic costs of water extraction may rise as a result of groundwater level declines. Both urban and rural people may experience financial hardship as a result, with rural areas frequently suffering the most from water scarcity. Furthermore, regions that formerly depended on groundwater for their livelihoods would find it extremely difficult to continue their economic and agricultural endeavors. Telangana Yearbook, Regional GroundWater Body, 2013–2022. The essential element for life is water. Many nations have experienced severe problems with water quality and quantity over recent years. The UN designated 2005–2015 as a decade of water, indicating that the world community recognizes a shortage of water (Glendenning 2009). By 2050, almost 2000 million people would be living in areas with high water stress. In many urban areas of the developing world, groundwater—the biggest freshwater reserve on Earth—is heavily mined. The excessive and ongoing use of water from the ground in urban settings frequently outpaces the slow process of natural replenishing of groundwater reservoirs. As a result, the levels of groundwater drop and groundwater resources are depleted, which causes a number of annoying issues like decreased well yields, subsidence of the ground, and saltwater intrusion, particularly in coastal locations. The depleted groundwater aquifers must be artificially recharged in order to overcome these severe environmental effects and to ameliorate the groundwater status.

IV. PROPOSED METHODOLOGY

The methodology includes the process of selecting an appropriate model for urban areas hydrology and rainwater collection design. These models may include the Green-Ampt model, the Soil Conservation Service's (SCS) model, or more sophisticated models like the Storm Water Management Model (SWMM) and the Hydrology and Hydrologic Modeling System (HEC-HMS). Finding the catchment areas for the flyovers, which would include pavement along with other structural components, is the initial step in this research. Rainfall data and surface characteristics like permeable and roughness are used to calculate runoff quantities. Designing the hydraulic frameworks, storage facilities, or containers, and reservoirs which will be incorporated into the flat system, together with their dimensions and operational circumstances, is the next step. The essential treatment steps will be described, along with any potential water contamination caused by flyovers and roads. The effectiveness of total volume and maximum rate of runoff reduction, as well as the effectiveness of rainwater extraction and stored volume, will all be examined and described. In conclusion, interest will use a cost-benefit analysis to support the economics of carrying out the same tasks as those previously indicated at the rates, its utilization, and the potential maintenance and installation fees.

A software application called Visual MODFLOW makes it possible to create and simulate a water flow model for groundwater systems under a variety of stressful circumstances, such as the total expected demand, which is based on groundwater pumping and recharging rate. The goal is to estimate potentiometric surface fluctuations within multiple management regimes by simulating and predicting underground water flow patterns and levels, along with heads in both space and time, and evaluating the impact of groundwater well depletion and recharge on flow regimens. Open source Geographic Information System (GIS) software called QGIS can be used to create the study area's base map, which is then imported into Visual MODFLOW. The study site's regions of interest are delineated using a grid that measures 100 m by 100 m. It is true that the borders between active and inactive cells—also known as flow boundaries and without flow boundaries—are always present. Groundwater layer thickness and number are determined. This phase also includes monitoring water sources and extracting boreholes with their parameters, like the screen's height and the well's maximum depth. Groundwater characteristics such as conductivity of water, porosity, specific yield, transmission, and river levels are defined based on published data. Predicted values of evapotranspiration, pumping rates, and rainfall recharge for the whole research region are fed into the model. Iteratively, model parameters are "fitted" to the information until an acceptable model-data fit is obtained. A statistical analysis is conducted on the measurement performances in both the constant state and the transitional state. The model is then validated by looking at how well the model's outputs match the data inputs. The regional groundwater level is simulated using the model developed prior to RWH (using only natural recharge), and the head compared against the real head. The function of RWH is indicated by the difference between the two heads. The simulation is also used to forecast the aquifer's hydrogeological conditions in the future based on three different pumping and recharging scenarios.

V. RESULT AND DISCUSSION

Lithological Formation

The conceptual MODFLOW model of the hydrological system was created according to the lithological formations in the city. Although the formations in the city differ from place to place, the general structure includes an abundance of weathered and crystalline granite. The top layer, which is modelled to be 20 meters thick, consists mainly of weathered granite mixed with clay, quartz and other minerals. This top layer acts as a shallow aquifer for groundwater. Beneath it is the hard bedrock made up of crystalline pink and grey granite ranging from tens to hundreds of meters.

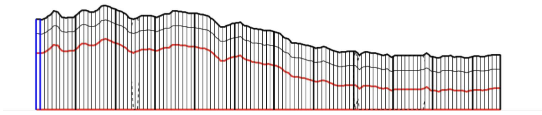

Fig 3. Lithological cross - section of study area

Base Map

Fig 4., represents the study area. A 37 km² area in Hyderabad, Telangana, identified as the target region for implementing a rainwater harvesting system using flyovers. This area is geographically defined using the WGS84/ UTM Zone 44N coordinate system (EPSG: 32644) for horizontal measurements and the EGM96 orthometric height system for vertical coordinates, ensuring precise mapping and elevation analysis.

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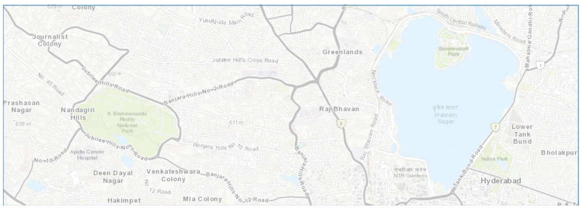

Fig 4. Labelled map of study area

The specific geographical coordinates of the model:

- **Longitude range**: 78.3993°E to 78.4968°E
- **Latitude range**: 17.4066°N to 17.4389°N

The selected coordinates include areas that are heavily populated and have flyover infrastructure already in place, which qualifies them for the suggested sustainable urbanization project. Because it enables precise assessment of surface water flow, drainage capacities, and potential rainwater storage, this geographic data serves as the foundation for hydrological simulations following the proposed methodology.

MODFLOW Model

The mode consists of a 117 column and 39 row grid where every grid cell is sized at 100m x 100m. This grid follows the same coordinate system as the base map. The model includes necessary packages for the boundary conditions used in the study:

- Evapotranspiration with Segments (ETS) Package: Simulates groundwater loss due to evapotranspiration, varying based on water table depth, allowing for detailed control of ET rates.
- Recharge (RCH) Package:Adds water to the groundwater system by simulating recharge from natural or artificial sources, such as rainfall infiltration or irrigation.
- Wells (WELL) Package :Simulates groundwater extraction or injection from wells by specifying rates at model grid cells.

The stress period of this study model is set at 24 hours. The study is performed using the ModelMuse GUI for MODFLOW 6.

Elevation Data

The elevation data for the study region is collected from Opentopography in GeoTiff format. The same data is converted to ASCII format using a GIS software in order to be compatible with MODFLOW. The Digital Elevation model is then imported to MODFLOW to assign topographic elevation data to the grid.

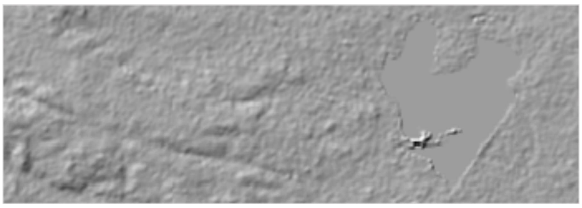
Fig 5. Digital Elevation Model of study area

Water Bodies Data

Natural and artificial water bodies in an area significantly impact its groundwater flow. It is, thus, necessary to incorporate this data into our MODFLOW model. Using open-source databases like Overpass Turbo, this data can be extracted and preprocessed using a GIS software. A total of 30 natural and artificial water bodies are found within the study area as shown in figure 6. which were converted into individual shapefiles to be imported in MODFLOW.

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Fig 6. Vectorized water bodies and flyovers

Flyovers Data

The study focuses on utilizing the prebuilt drainage system of flyovers within the study region in a way that allows rainwater to be injected directly into the groundwater aquifers. The position and dimensions of all flyovers inside the study region is obtained by querying the OpenStreetMap (OSM) in the Overpass Turbo database. In total, 7 flyovers were extracted as vertices which were later converted to a cluster of 5 recharge points using QGIS software. The remaining 2 flyovers were not considered in the model due to insufficient dimensional data.

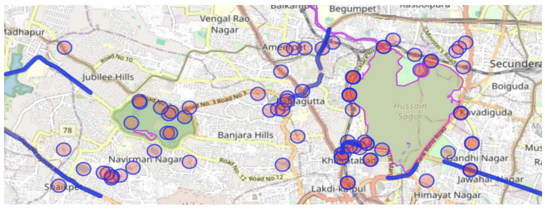

Fig 7. Water bodies and flyovers OSM

Boundary Conditions

In order to run a MODFLOW model, some boundary conditions need to be assigned to its components. The entire grid is assigned a RCH condition which is calculated using the area of the grid (in sq meters) and the annual average rainfall rate of 810mm for the entire city. This value is estimated as 3.7mm/day for the study grid. The ETS is assumed to be 25% of the total recharge of the grid as standard.

Every individual water body area is measured and boundary conditions for RCH and ETS are fed to the program accordingly.

The model assumes that groundwater is the only source of water for consumption, residential and industrial purposes within the study region. In order to simulate the extraction of water for these purposes, the model includes three extraction wells in selected regions within the grid. These regions were selected on the basis of surface elevation where the first well is situated close to the low-lying lake, the second well is situated in the high-lying areas on the map and the third well is situated at a mean elevation of the previous wells. Fig 8 shows the defined wells highlighted in green.

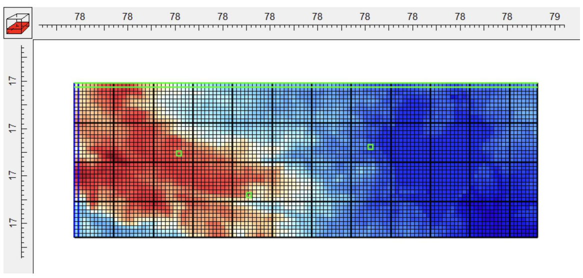

Fig 8. Defined Wells in MODFLOW model

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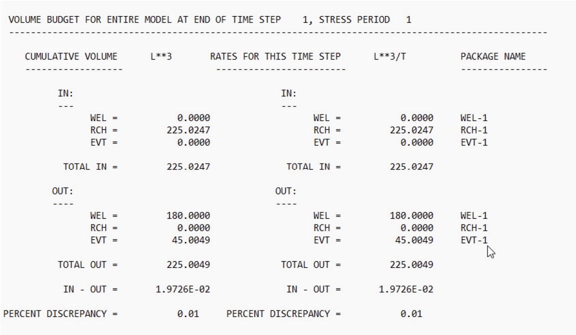
The extraction wells are assumed to be pumping 180m^3/day of groundwater. This quantity was calculated using factors like estimated water requirement per person and thus may differ from the actual requirement for the study area due to factors like change in population density and seasonal change.

Control Simulation

The control simulation involves running the MODFLOW model without incorporating the impact of flyovers acting as rainwater catchment areas. This allows us to calibrate the boundary conditions and evaluate the overall correctness of the model inputs provided. The control simulation also allows us to observe the equilibrium in terms of groundwater consumption and recharge.

The control simulation was run for 1 stress period, i.e., 24 hours which resulted in the volume budget for the model at the end of the simulation getting a discrepancy of 0.01%, where a total groundwater inflow of 225.0247 litres was observed in the stress period along with an outflow of 225.0049 litres.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VOLUME BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
---------------------------------------------------------------------------

   CUMULATIVE VOLUME      L**3       RATES FOR THIS TIME STEP      L**3/T          PACKAGE NAME
   -----------------                 ------------------------                      ----------------

         IN:                                  IN:
         ---                                  ---
               WEL =           0.0000               WEL =           0.0000         WEL-1
               RCH =         225.0247               RCH =         225.0247         RCH-1
               EVT =           0.0000               EVT =           0.0000         EVT-1

          TOTAL IN =         225.0247          TOTAL IN =         225.0247

        OUT:                                 OUT:
        ----                                 ----
               WEL =         180.0000               WEL =         180.0000         WEL-1
               RCH =           0.0000               RCH =           0.0000         RCH-1
               EVT =          45.0049               EVT =          45.0049         EVT-1

         TOTAL OUT =         225.0049         TOTAL OUT =         225.0049

          IN - OUT =       1.9726E-02          IN - OUT =       1.9726E-02

PERCENT DISCREPANCY =           0.01     PERCENT DISCREPANCY =           0.01
```

Fig 9. Control Simulation Results

This control simulation provided validation for all the input parameters used as boundary conditions for the model. These results can also be used to justify the declining water table depths mentioned in the problem statement since the model does not take into account factors like increasing population in urban areas and declining recharge rates due to runoff and urbanisation.

Simulation for Impact of Rainwater Harvesting using Flyovers

Running the simulation for rainwater harvesting using flyovers as catchment areas involved collection of data of 5 flyovers as shown in fig 10., within the study area from the OSM database. This data is then processed in a GIS software to make it compatible with MODFLOW.

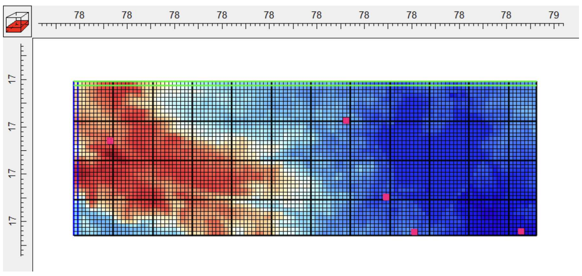

Fig 10. Flyover recharge points in MODFLOW model

The flyover dimensions required for the boundary condition include their length and width. Using this data, the calculated surface area of the flyovers turned out to be ~1,35,600 m^2. This surface area

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processed with the annual average rainfall of 810mm was used as RCH condition in the MODFLOW model.

The rainwater harvesting simulation was run for 1 stress period, i.e., 24 hours which resulted in an increase in the volume budget for the model by around 2.4% as compared to the control simulation running the same inputs. The water table height was also observed to be increased significantly around the rainwater recharge points with an average predicted hydraulic head of 0.3 meters. In future, these results can further be improved by incorporating a range of extraction and observation wells into the study area and by increasing the stress periods of simulation from days to years.

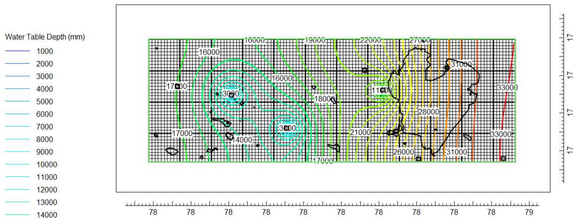

Fig 11. Simulated Hydraulic Head

The study demonstrated that integrating rainwater harvesting systems into flyovers can significantly address Hyderabad's water scarcity and urban sustainability challenges. The simulation results revealed that the proposed system efficiently captured a substantial proportion of rainwater runoff from the study area's flyover network. In terms of the environment, the rainwater harvesting project supports the objectives of urban sustainability by reducing surface runoff, which frequently introduces contaminants into waterways. The project also demonstrated the ability to regulate peak flow rates, lowering urban flood risk by 30% during high rainfall events.

The study also highlights important obstacles and constraints. For example, strong filtration and treatment systems are required prior to groundwater recharge due to the quality of captured rainwater, which is contaminated by urban pollutants such as vehicle emissions and road debris. Furthermore, the upfront costs of setting up and maintaining this kind of infrastructure are a major obstacle, especially in towns with tight budgets. Governmental policy frameworks that require the incorporation of rainwater collection into new urban infrastructure projects and offer tax breaks or subsidies for retrofitting existing flyovers could help address these issues.

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