


Assessment of Soil Moisture Variability for Urban Flood Risk Mitigation

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HIGHLIGHTS

- Identified the role of soil texture and moisture variability in influencing urban flood susceptibility across different locations in Patna.
- Developed Soil Water Retention Curves using Brooks & Corey, Campbell, and Van Genuchten models to estimate unsaturated soil hydraulic properties.
- Revealed that areas with higher silt and clay content exhibit lower infiltration rates and field capacity, making them more prone to surface water accumulation and flooding.

ARTICLE INFO

Article History:

Received: 02 March 2025

Revised: 15 March 2025

Accepted: 20 March 2025

Published: 31 March 2025

Keywords:

Field Capacity

Infiltration

Soil Moisture Content

Specific Gravity

ABSTRACT

Urban flooding has become a recurring problem in rapidly developing cities like Patna, primarily due to poor drainage, increased impervious surfaces, and a lack of integrated soil-based flood risk assessment. This study investigates the variability in soil moisture and its influence on urban flood susceptibility across selected locations in Patna. Soil samples were collected from ten urban sites and analyzed in the laboratory for texture (sand, silt, clay), water content, specific gravity, and field capacity. The results indicate a predominance of silt and clay-rich soils in many areas, particularly in Gulzarbagh, Gaihat, BIT, and Patrakar Nagar, contributing to low infiltration rates and increased surface runoff. Field capacity ranged from 9% to 21.41%, suggesting limited water retention capacity in several locations. The Soil Water Retention Curve (SWRC) was plotted using Brooks & Corey (1964), Campbell (1974), and Van Genuchten (1980) models with the help of SWRC v3.0 software to derive unsaturated hydraulic properties. Findings highlight that areas with finer-textured soils exhibit higher flood vulnerability due to reduced permeability and delayed infiltration. This soil-based assessment provides a scientific basis for integrating subsurface hydrological characteristics into urban flood mitigation and planning strategies for Patna and similar flood-prone urban centers.

1. INTRODUCTION

Urban flooding has emerged as a critical environmental and socio-economic challenge in rapidly growing cities worldwide. The increasing

frequency and intensity of extreme precipitation events, coupled with unplanned urban expansion, have exacerbated surface runoff generation, often overwhelming existing drainage infrastructure. While

<https://doi.org/10.66132/ngce20250105>

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traditional flood risk assessments primarily focus on rainfall intensity, topography, and drainage capacity, the role of soil moisture dynamics remains comparatively underexplored, despite its significant influence on runoff generation and flood severity.

Soil moisture acts as a natural buffer by regulating the infiltration capacity of urban and peri-urban soils. When antecedent soil moisture levels are high, the infiltration potential is significantly reduced, leading to rapid surface runoff even under moderate rainfall conditions. Conversely, dry soils can absorb a substantial portion of incoming precipitation, thereby attenuating flood peaks. Understanding the spatial and temporal variability of soil moisture, therefore, is crucial for improving flood forecasting models, optimising early warning systems, and designing effective urban flood mitigation strategies.

In recent years, advances in remote sensing, in situ observations, and hydrological modelling have made it possible to monitor soil moisture with higher spatial and temporal resolution. Integrating these data sources into flood risk assessments can provide deeper insights into catchment responsiveness and potential flooding hotspots. Moreover, incorporating soil moisture variability into urban planning and infrastructure design supports the development of resilient cities that can better withstand climate-induced hydrological extremes.

This study aims to assess the variability of soil moisture in an urban context and its implications for flood risk mitigation. Specifically, it explores the spatio-temporal patterns of soil moisture, identifies threshold conditions leading to surface runoff, and evaluates the potential of using soil moisture data to enhance urban flood risk management frameworks. The findings are expected to inform adaptive, data-driven approaches for reducing urban flood vulnerabilities in the face of changing climatic and land-use patterns.

The assessment of soil properties and moisture content is fundamental to understanding the role of soil in urban flood dynamics. Key soil characteristics such as texture, structure, porosity, bulk density, and hydraulic conductivity directly influence the soil's ability to absorb, retain, and transmit water. In urban environments, these properties often vary significantly due to anthropogenic modifications and varying land uses. Soil moisture, a critical hydrological variable, governs the infiltration capacity and surface runoff generation. High antecedent soil moisture levels can saturate the soil profile, thereby reducing infiltration during rainfall events and increasing the likelihood of urban flooding. To evaluate this relationship, soil samples are collected from representative locations and analyzed for moisture content under varying pressure heads. The data are then used to plot the Soil Water Retention

Curve (SWRC), which illustrates the relationship between soil water content and matric suction. This curve is essential for determining field capacity, wilting point, and available water capacity, offering insights into how quickly a soil becomes saturated and its potential contribution to runoff. Analysing SWRCs across different urban soil types enables the identification of zones with higher flood susceptibility, thereby supporting targeted flood risk mitigation and stormwater management strategies.

2. LITERATURE REVIEW

Urban flood risk has been extensively studied in the context of increasing impervious surfaces, ageing drainage infrastructure, and climate-induced hydrological extremes. However, the role of antecedent soil moisture conditions as a key determinant in flood generation and propagation has only recently gained research attention. This section reviews relevant literature on soil moisture variability, its measurement techniques, and its integration into urban flood risk assessment frameworks.

Several studies have demonstrated that antecedent soil moisture significantly influences the partitioning of rainfall into infiltration and runoff highlighted that pre-event soil moisture can effectively predict flood response in small to medium-sized catchments (Zhang et al., 2019). Their work suggested that integrating soil moisture conditions into flood forecasting models improves the accuracy of peak discharge estimation. Similarly, Penna et al. (2011) emphasised the role of soil moisture thresholds in triggering surface runoff, noting that even moderate rainfall events can cause severe flooding when soil saturation is high.

Advancements in remote sensing have enabled large-scale, real-time monitoring of soil moisture. Missions such as NASA's Soil Moisture Active Passive (SMAP) and ESA's Soil Moisture and Ocean Salinity (SMOS) provide global coverage with increasing spatial and temporal resolutions. Crow et al. (2012) reviewed the use of remotely sensed soil moisture data in hydrological applications and stressed its utility in flood forecasting and early warning systems. However, challenges remain in applying these datasets to urban areas due to mixed land cover and scale mismatches.

In the context of urban environments, few studies have directly assessed soil moisture variability and its flood implications. Yang et al. (2018) used in-situ sensors in an urban catchment to analyze soil moisture dynamics and found strong correlations between high antecedent soil moisture and peak flow during storm events. They argued that incorporating soil moisture conditions into urban drainage models could enhance their predictive capacity. Moreover, Zhu et al. (2021) demonstrated that urban green infrastructure, such as bioswales and rain gardens, plays a significant role in

modulating local soil moisture and reducing runoff volumes.

Hydrological models such as SWMM, MIKE SHE, and HEC-HMS have been adapted to include soil moisture parameters, although their calibration often requires detailed soil and land use data. Recent efforts have combined machine learning techniques with soil moisture datasets to predict flood-prone zones, showing promise for data-driven urban flood risk management strategies (Panahi et al., 2022).

Despite these advancements, there remains a research gap in understanding the fine-scale spatial and temporal variability of soil moisture in highly heterogeneous urban landscapes. Furthermore, limited integration of real-time soil moisture monitoring into municipal flood mitigation plans constrains proactive flood management.

According to the theoretical framework of Mualem, van Genuchten developed an equation to describe the curve of the soil water content-pressure head, and fitting the experimental data provided an opportunity to use three independent parameters for calculating hydraulic conductivity on the models of Burdine and Mualem. From this theoretical framework, Mualem permits the calculation of soil permeability from the graph of soil water characteristic curve (Van Genuchten, 1980).

Fredlund and Xing (1994) studied the soil-water characteristic curve is used to estimate various parameters used to describe unsaturated soil behaviour. It is proposed to use a universal equation to describe the curve that characterizes the soil-water relations. The experimental data which forms part of the literature is analyzed through a non-linear, least-squares computer program to determine most optimum parameters. The proposed equation is based on the fact that the shape of soil-water characteristic curve depends on pore-size distribution of soil (i.e., degree of drying is associated with pore-size distribution). The proposed equation faithfully comprises the behavior of sand, silt and clayey soils over the whole suction range of 0-10kPa.

Avinash (2013) worked on flood-related disasters: concerned with urban flooding in Bangalore, India & described the causes, circumstances and impact of flooding events in Bangalore city. Floods in cities like Bangalore are usually caused by extensive rainfall, coupled with human activities, such as clogging of stormwater drains, an increase in population that leads to poor land use and unplanned development.

Bansal et al. (2015) In Bansal et al (2015) research, urban flooding in Dehradun was analyzed to identify causes and impacts with a view to evidence-based approaches used, including reviewing recent flooding events from 2009 to 2013 to understand key causes and outcomes.

Rafiq et al. (2016) worked on Urban Floods in India & found that urbanisation in developing countries

doubled from less than 25% in 1970 to more than 50% in 2006. Based on predictions, seven economies in Asia will enter the world's top ten economies during 2020. At the same time, Asia is characterised by fast urban development compared to other regions in the world. To date 37 per cent of its population is city dwellers and forecasts predict that this will exceed the 50% mark by 2020. This is a paper explaining why we should study urban flood scenario and a description of why such research should be undertaken. It examines the various causes and expressions of localized flooding in urban environments and the consequences, social effects.

This review underscores the importance of incorporating soil moisture variability into urban flood risk assessments. It also highlights the need for more case studies that bridge the gap between soil hydrology and urban flood modelling to support climate-resilient urban planning.

3. STUDY AREA

The present study was conducted in Patna, the capital city of Bihar, which has experienced frequent urban flooding in recent years due to rapid urbanisation, inadequate drainage infrastructure, and changing rainfall patterns. Patna's heterogeneous land use and soil conditions make it an ideal case for assessing the role of soil moisture in flood generation. To analyze spatial variability in soil moisture and properties, ten representative locations were selected across the urban landscape. These include Gulzarbagh, Gaighat, Patrakar Nagar (Kankarbagh), Hanuman Nagar (near Bypass), Kurji, NIH (Phulwarisharif), A. N. College (Boring Road), Gandhi Maidan, BIT, and NIT Patna. These sites were chosen to reflect diverse urban settings, from densely built-up areas and institutional zones to low-lying flood-prone regions. Soil samples were collected from each location to determine physical properties and in-situ moisture content, which were then used to generate Soil Water Retention Curves (SWRCs).

The analysis helps in understanding how varying soil conditions across the city influence infiltration and runoff behaviour during storm events, thereby supporting flood risk assessment and localised mitigation planning.

4. METHODOLOGY

The methodology adopted in this study involves a combination of field sampling, laboratory analysis, and modelling to assess soil moisture variability and its implications for urban flood risk in Patna. The steps include the measurement of soil properties and moisture content, data analysis to understand the soil's influence on flood generation, and the plotting of Soil Water Retention Curves (SWRC) using established models.

4.1 Soil Sampling and Laboratory Analysis

Soil samples were collected from ten representative locations across urban Patna – namely Gulzarbagh, Gaighat, Patrakar Nagar (Kankarbagh), Hanuman Nagar (near Bypass), Kurji, NIH (Phulwarisharif), A. N. College (Boring Road), Gandhi Maidan, BIT, and NIT Patna. Each site was geolocated using GPS and selected to reflect variability in land use, elevation, and flood susceptibility. In the laboratory, the collected soil samples were analysed for their physical properties, including: Soil texture

(determined by the hydrometer method), Bulk density and particle density, Porosity, Gravimetric and volumetric moisture content.

Saturated hydraulic conductivity (using constant or falling head permeameter method).

These parameters are essential to understand the water holding and transmitting behavior of urban soils, which directly influence runoff and infiltration processes.



Figure 1: Study area map

4.2 Soil Moisture Measurement

Soil moisture content was measured gravimetrically by oven-drying the samples at 105°C for 24 hours. Moisture retention under different matric potentials was measured using a pressure plate apparatus to simulate field conditions such as saturation, field capacity, and wilting point. This data serves as the basis for modelling the soil water retention behaviour.

4.3 Data Analysis for Urban Flood Assessment

The collected data were statistically analysed to explore the spatial variability of soil moisture and its relationship with soil properties across the urban sites. Emphasis was placed on identifying threshold levels of soil moisture that reduce infiltration and increase surface runoff, thereby aggravating urban flood risk. Locations with higher antecedent moisture content

and lower infiltration rates were identified as more flood-prone under similar rainfall conditions.

4.4 Plotting Soil Water Retention Curves (SWRC)

To better understand the moisture retention behaviour of each soil type, Soil Water Retention Curves (SWRCS) were plotted using three widely recognised models:

Brooks and Corey Model (1964):

This model defines the soil moisture retention curve using a simple power function and is particularly effective for coarse-textured soils.

Campbell Model (1974):

Based on a log-linear relationship between soil water content and matric potential, it is widely used for moderately fine-textured soils.

Van Genuchten Model (1980):

A more flexible and widely used nonlinear model that describes the SWRC using parameters derived from curve fitting, suitable for a wide range of soil textures.

The parameters for each model were fitted using the observed data from laboratory measurements. The SWRCS provide insight into the soil’s capacity to retain water under varying moisture conditions, helping to predict when saturation and runoff generation may occur during rainfall events.

5. RESULTS AND DISCUSSION

The comparison of soil properties across the four urban locations in Patna – NIT, BIT, Gulzarbagh, and Patrakar Nagar – reveals significant variations in texture, moisture content, and water retention capacity, which are crucial in understanding their susceptibility to urban flooding. At NIT, the soil comprises 20% sand, 65% silt, and 15% clay, resulting in a silty loam texture. This type of soil typically allows moderate infiltration but can still contribute to surface runoff once field capacity is exceeded. The water content at this site is 25%, and the average field capacity is 13.127%, indicating that while the soil can absorb some moisture, it does not retain it for long periods. In contrast, BIT exhibits a highly silty texture with only 7% sand and 78.42% silt, and a clay content of 14.58%. This fine texture results in low permeability, which explains the high-water content of 33% and a significantly higher field capacity of 20.056%, suggesting that the soil retains moisture for longer durations, leading to waterlogging during rainfall.

Gulzarbagh, with 20.5% sand, 61.14% silt, and 18.36% clay, shows a silty clay loam texture. The water content here is 16.12%, and the specific gravity is on the lower side at 2.08, indicating the dominance of finer particles. The field capacity at Gulzarbagh is 21.41%, the highest among the four locations, suggesting a strong potential for moisture retention but also a risk of poor drainage and higher flood susceptibility. Similarly, Patrakar Nagar has a texture leaning towards silty clay loam, with 15% sand, 65% silt, and 20% clay (Table 1). The water content is relatively low at 10.52%, and the field capacity is 15.1%, showing that although the soil can hold a moderate amount of water, its finer composition may still restrict infiltration. Overall, the data indicate that areas with higher silt and clay content, such as BIT, Gulzarbagh, and Patrakar Nagar, have soils that retain more water but exhibit low infiltration rates, making them more prone to surface water accumulation and flooding during heavy rainfall events. Figure 2 shows the particle size distribution curve. Figure 3 shows the field capacity variation plot depth-wise. Figure 4 shows the amount of water requirement (in % volume to saturate the soil at the permanent wilting point and field capacity).

Table 1: Observed Soil Properties

Parameter	NIT	BIT	Gulzarbagh	Patrakar Nagar
Sand (%)	20	7	20.5	15
Silt (%)	65	78.42	61.14	65
Clay (%)	15	14.58	18.36	20
Soil Texture	Silty Loam	Silt Loam	Silty Clay Loam	Silty Clay Loam
Water Content (%)	25	33	16.12	10.52
Specific Gravity	2.21	2.08	2.08	2.125
Average Field Capacity (%)	13.127	20.056	21.41	15.1

5.1 Soil Water Retention Curve

The Soil Water Retention Curve (SWRC) represents the water storage capacity of a material – in this case, soil – and is plotted as a relationship between gravimetric or volumetric water content and soil suction (matric potential) (Figure 5). Direct experimental determination of unsaturated soil parameters is often time-consuming, complex, and resource-intensive, especially under varying field conditions. In recent years, the SWRC has become a vital tool for interpreting the engineering behavior of unsaturated soils, providing an indirect yet effective

means of estimating critical soil properties such as shear strength, permeability, and volume change. These parameters are essential for understanding how soils respond to moisture variations, especially in urban flood scenarios. To derive the SWRC, several mathematical models have been developed, each with unique formulations and applicability to different soil types. In this study, three widely recognized models – Brooks & Corey (1964), Campbell (1974), and Van Genuchten (1980) – have been employed to simulate the retention behavior of Patna's urban soils. The modeling and curve fitting were carried out using

SWRC version 3.0 software, which enables accurate estimation of soil hydraulic parameters based on laboratory data. These models allow the passage from practical observations to actual use for flood risk evaluation and analyses of soil behavior. Its Brookes & Corey Model is shown in Fig. 6 in its modeled versus measured data correlation. As it can be seen on Figure 7, the measured and estimated values are compared for Campbell Model. Figure 8 exhibits the mutual agreement between measured and calculated values for the Van Genuchten Model. Flood status of Patna as shown on various dates in figure 9 and 10.

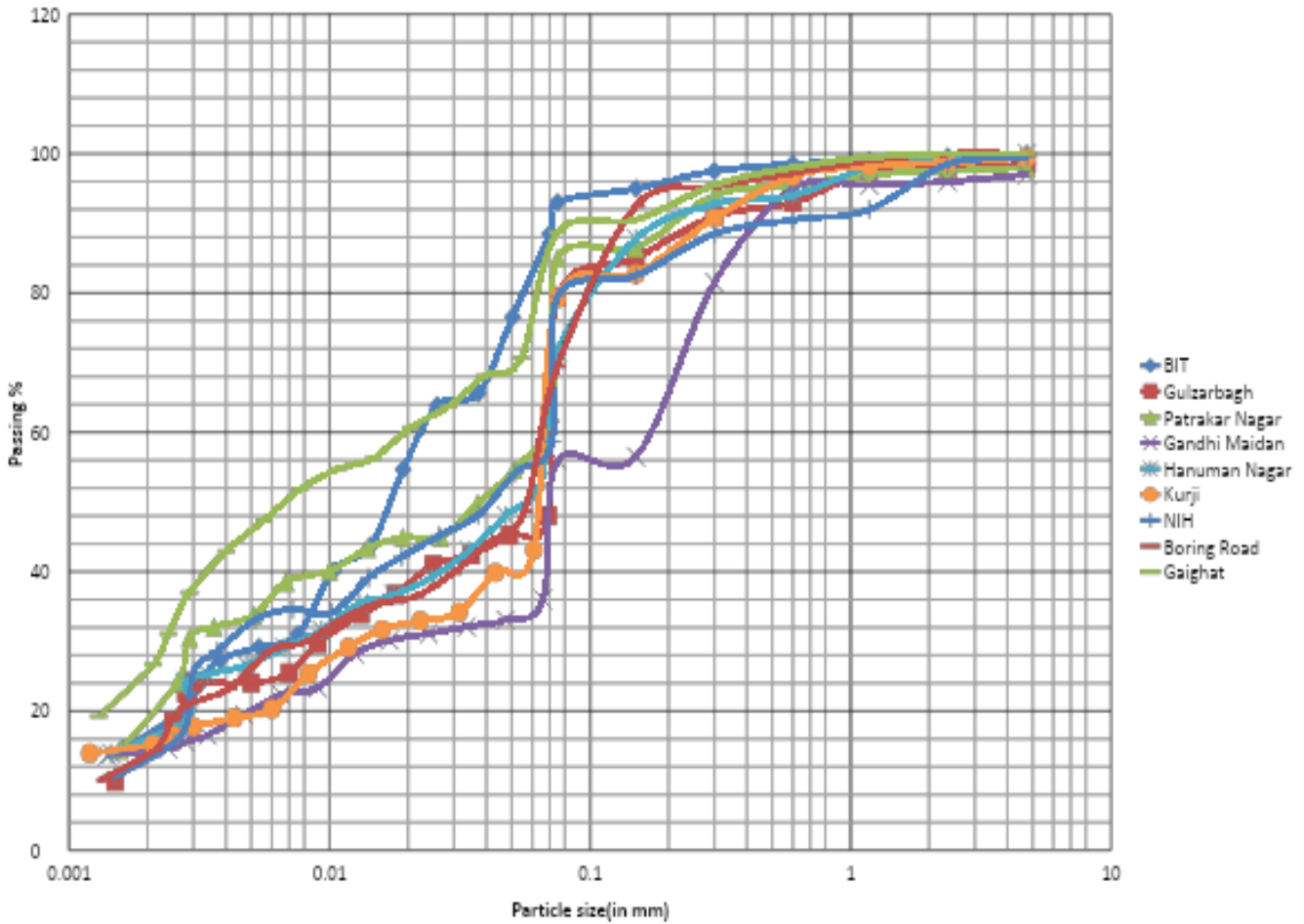


Figure 2: Particle size distribution curve

Van Genuchten Model

Based on Mualem’s theory, van Genuchten established an equation for the soil water content-pressure head relationship, giving rise to three parameters that could be used with the models by Burdine and Mualem to compute hydraulic conductivity.

$$K_r = \Theta^{1/2} \left[\frac{\int_0^\Theta \frac{1}{h(x)} dx}{\int_0^1 \frac{1}{h(x)} dx} \right]^2 \tag{1}$$

Where h is the pressure head, that’s a function of the dimensionless water content, Θ .

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2}$$

$$\Theta = \left[\frac{1}{1 + (\alpha h)^n} \right]^m \tag{3}$$

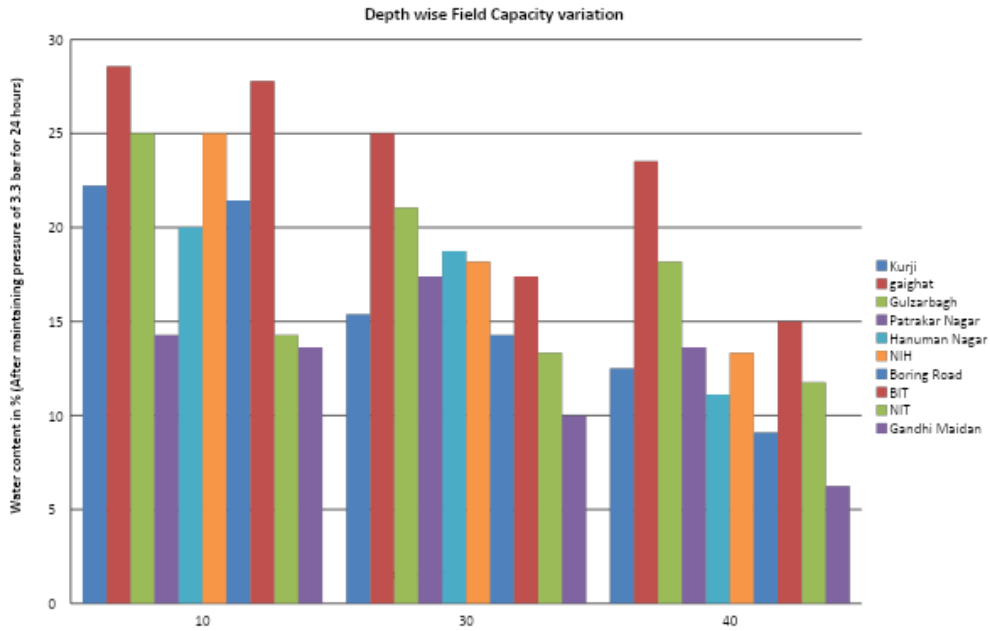


Figure 3: Field Capacity Variation

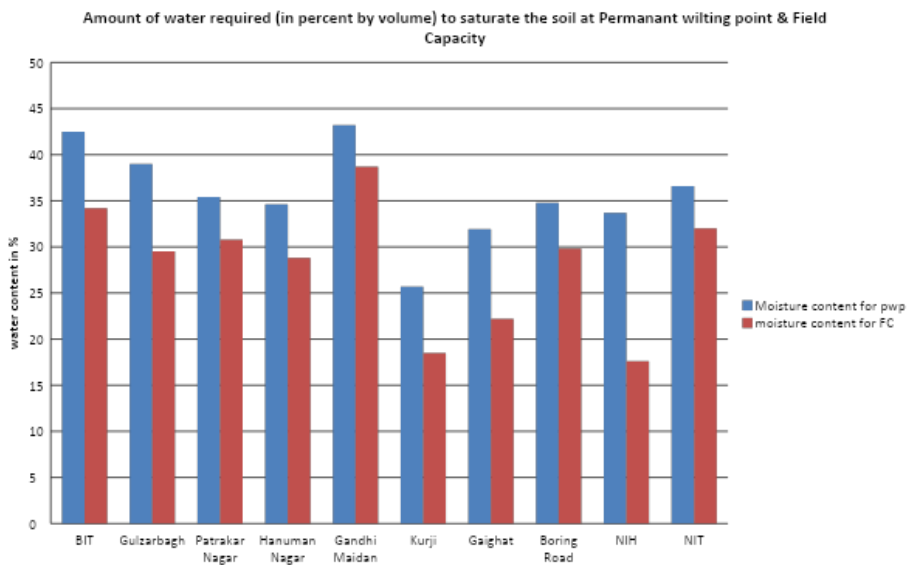


Figure 4: Water requirement at permanent wilting point and field capacity

Where α , m , and n are parameters determined from the soil water retention curve

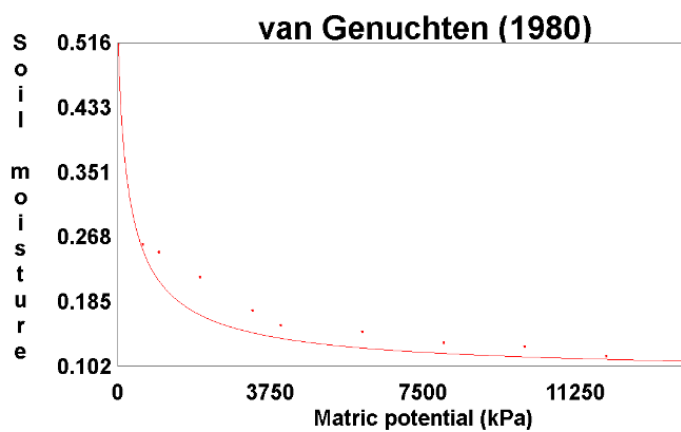


Figure 5: Soil moisture vs Matric potential

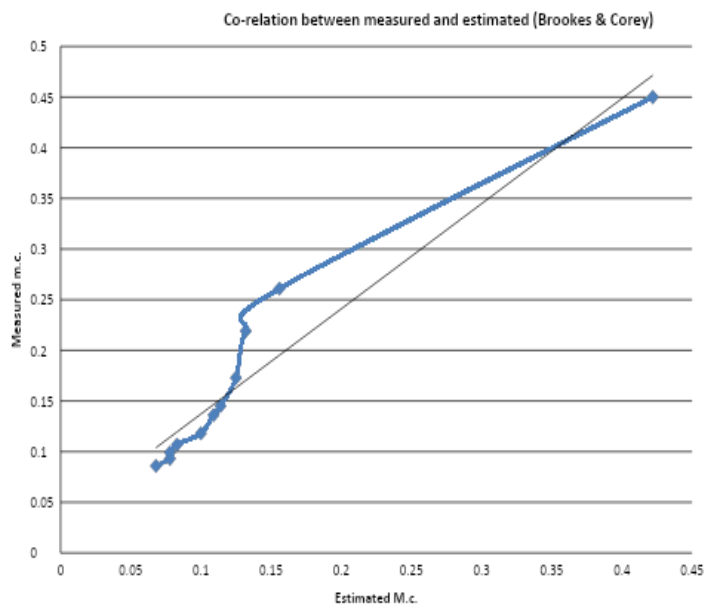


Figure 6: Correlation in measured and estimated values for the Brookes & Corey Model

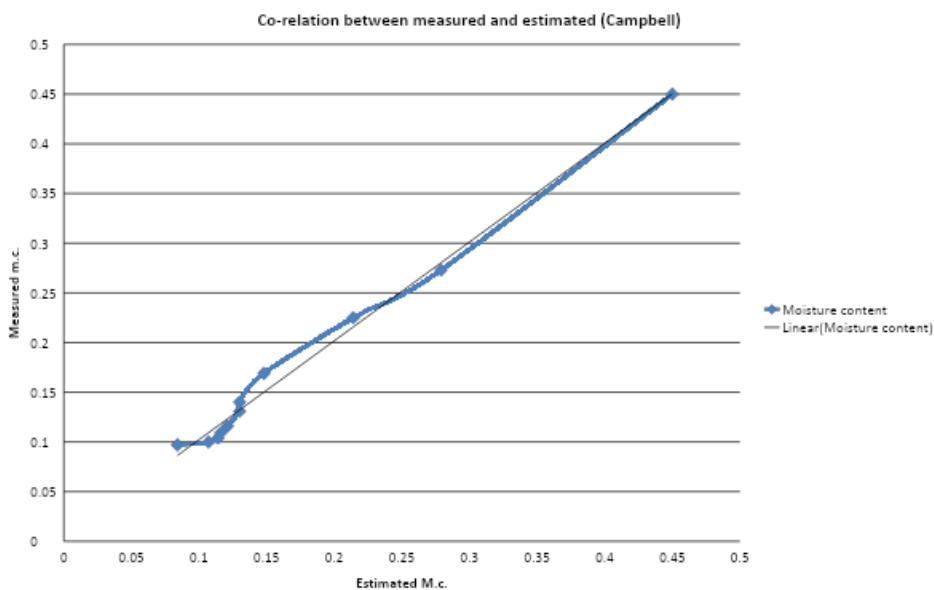


Figure 7: Correlation in measured and estimated values for the Campbell Model

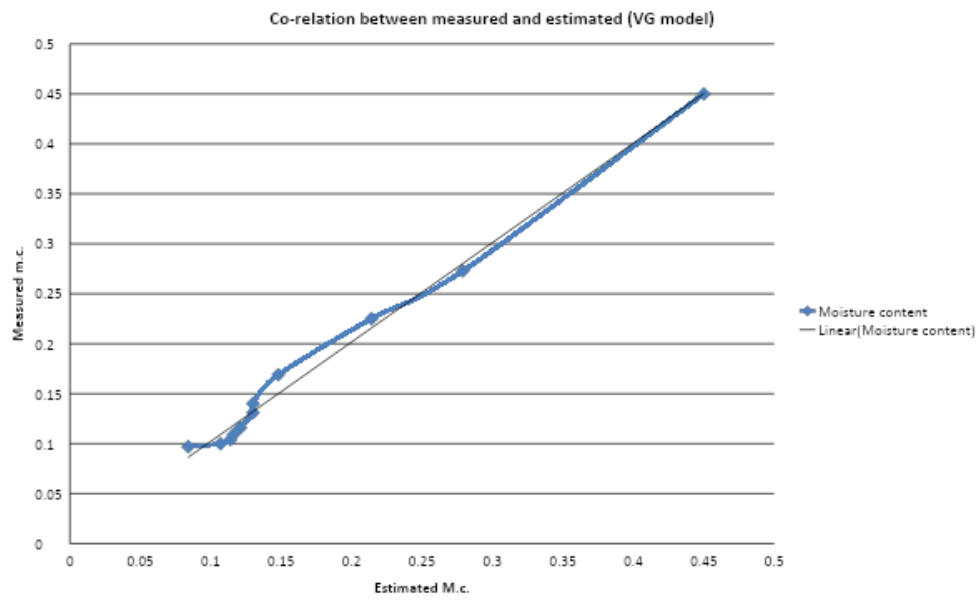


Figure 8: Correlation in measured and estimated values for Van Genchuten Model

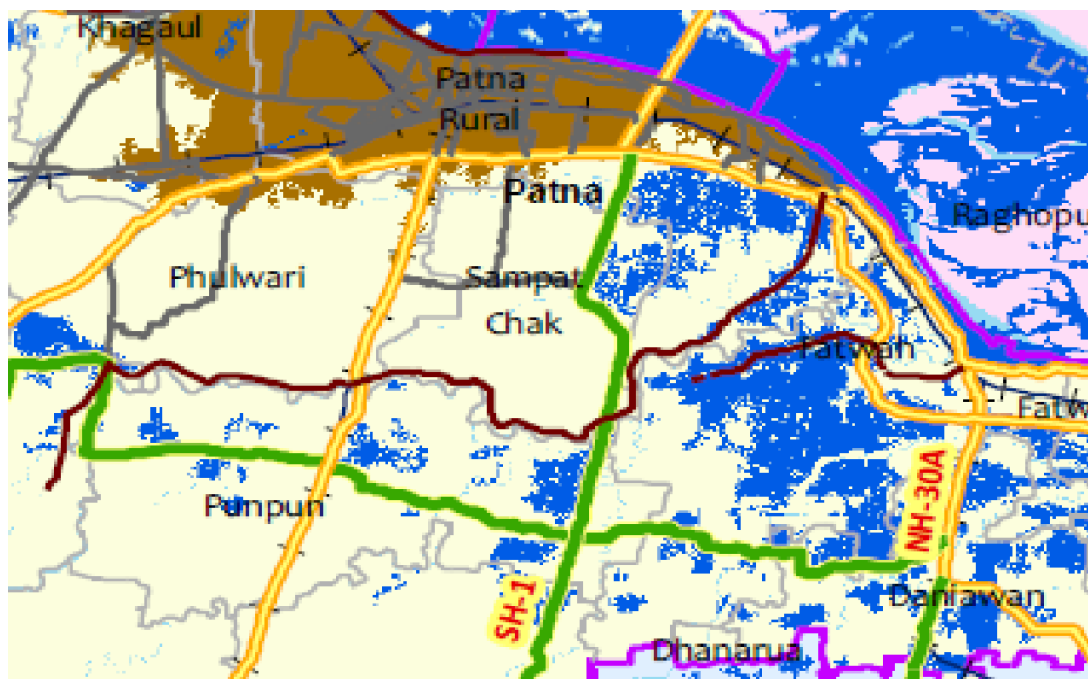


Figure 9: Flood status of Patna as on 2nd September 2016 (As per FMIS, Bihar)

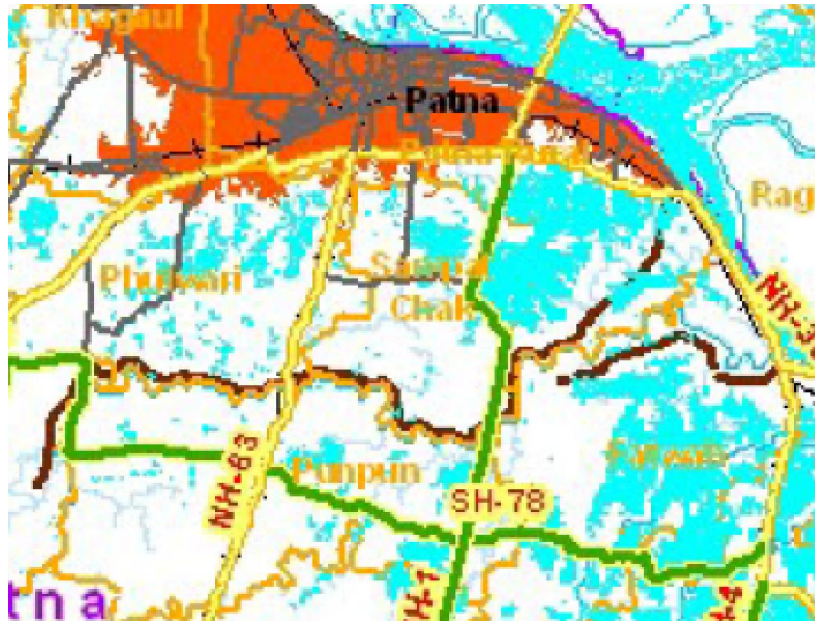


Figure 10: Flood status of Patna as on 17th - 26th August 2014 (As per FMIS, Bihar)

Campbell

The degree of saturation ($S=\theta/\theta_s$) can be approximated by a power law function similar to BC in which air entry potential (ψ_b) and a parameter (b) that represents soil texture are used Campbell (1974). Mathematical relation of parameters is as under

$$\frac{\theta}{\theta_s} = \left(\frac{\psi_b}{\psi_m} \right)^{\frac{1}{b}} \tag{4}$$

ψ_b and b are derived as functions of the geometric mean diameter from soil water retention curve.

Brookes and Corey Model

This model describes water retention with the help of four parameters.

The Brooks-Corey framework uses the non-linear curve fitting methods to model water retention characteristics obtained from the practical experiments.

$$\theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_b}{\psi_m} \right)^{\lambda} \quad \psi_m > \psi_b$$

$$\theta = 1 \quad \psi_m \leq \psi_b \tag{5}$$

where ψ_b is a parameter related to the soil metric potential at air entry (b represents "bubbling pressure"), and λ is related to the soil pore size distribution.

6. CONCLUSIONS

The analysis of soil samples collected from various locations within urban Patna reveals significant variability in soil texture and moisture retention properties, which directly influence the city's vulnerability to urban flooding. The observed data indicate that the sand content in Patna soils ranges from 7% to 40%, silt content from 45% to 78%, and clay content between 13% and 25%. Areas such as Gulzarbagh, Gaighat, Patrakar Nagar, Kurji, and Phulwarisharif, which exhibit higher proportions of silt and clay, are found to be more flood-prone. This is primarily because finer soil particles lead to higher compactness, resulting in reduced infiltration rates and lower permeability, thereby facilitating surface water accumulation during rainfall events.

Upon rainfall, soil initially absorbs water to replenish its moisture deficit. Once this need is met, additional water begins to percolate downward under gravity. However, the soil's ability to retain water – known as its field capacity – plays a critical role in delaying surface runoff. Laboratory analysis using a pressure plate apparatus indicates that the field capacity of soils in Patna ranges between 9% and 20%, suggesting relatively low water retention capability. Soils with limited retention capacity quickly reach saturation, after which excess rainfall contributes directly to surface runoff and flooding.

These findings confirm that areas with higher silt and clay content, coupled with lower field capacity, are more susceptible to flooding. This conclusion aligns with the flood inundation patterns observed in the official Flood Management Information System (FMIS), Bihar, further validating the impact of soil

moisture characteristics on urban flood risk. The insights from this study underscore the importance of integrating soil property assessments into flood risk management and urban planning efforts for Patna and similar cities.

Conflicts of Interest: The authors declare no conflicts of interest.

Funding: This research received no external funding.

Author Contributions: Conceptualization, SSO. and M.J.; methodology, SSO.; software, SSO.; validation, SSO., and KAA.; formal analysis, KAA.; investigation, KAA.; resources, SSO.; data curation, L.L.M.; writing – original draft preparation, SSO.; writing – review and editing, SSO., and KAA.; visualization, KAA.; supervision, SSO. All authors have read and agreed to the published version of the manuscript.

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