International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 • Website: www.ijfmr.com • Email: editor@ijfmr.com

An Integrated Hydrological Evaluation of the Subarnarekha River Basin: Measuring the Associated Effects of Human Caused Land Use Change and Climate Change

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Abstract

A thorough approach that simultaneously evaluates the effects of local, human-induced changes in land use land cover (LULC) as well as global climate influences is essential for understanding how vulnerable fresh water resources are in regions that experience monsoon rainfall. The increasing levels of carbon dioxide and other radiative trace gases have led to a significant rise in the earth's average surface temperature which in turn has altered the water cycle and result in extreme weather conditions such as prolonged droughts, intense flooding and shifts in river flow behavior. In this context, the study focuses on the important Subarnarekha River Basin, located in Ranchi, where the goal is to assess the combined impacts of climate change and fast-paced human activities such as deforestation, urban expansion, and the reduction of agricultural land, on the amount of water flowing through rivers. Water discharge, which refers to the total volume of water that passes through a specific point in a river or stream over a certain period, is a key measure in hydrology.

Keywords: Temperature, rainfall, water flow, climate change, Subarnarekha River, Ranchi, SWAT.

1. INTRODUCTION

A. Coupled Stressors in a Global Context

Assessing freshwater resource vulnerability in monsoon-dominated systems requires a comprehensive approach that considers both local human-driven land use changes and global climate forcing. The past century's rising global temperatures, driven by increasing CO_2 and other gases have altered the hydrological cycle, leading to more extreme weather events like droughts and floods [1]. With global warming projected to rise by 2°C to 5°C by the end of this century, understanding these impacts is crucial [1]. These global trends present severe regional challenges within the Indian subcontinent. India's extensive riverine networks are its primary water resource. However, the region has already experienced a temperature increase of approximately 0.87°C over the last century, coupled with variations in mean rainfall ranging from 6% to 15% from historical norms [1]. These resources face extreme strain due to the increasing demands of expanding urban, industrial, and agricultural sectors. Consequently, India's per capita water availability is projected to decline sharply from 1820m^3/person/year (2001-2019) to a concerning1140m^3/person/year by 2050 [1]. This anticipated scarcity highlights the urgent need for thorough, basin-scale hydrological modelling focused on the critical near-future era.

B. The Challenge of Integrated Hydrological Assessment

Addressing the challenge of distinguishing between the impacts of these two primary factors requires a comprehensive evaluation. Local anthropogenic factors like rapid urbanization and deforestation often exert a more immediate and substantial influence on short-term hydrological responses such as peak flow amplitude and flood occurrence [2]. In contrast, climate change shapes the long-term water availability environment. Human-induced landscape alterations can lead to increased peak flows and storm runoff [4]. Construction converting vegetated areas into impermeable surfaces boosts runoff volume and velocity exponentially, altering watershed hydrological parameters [2]. For policy-relevant projections in the Subarnarekha River Basin, integrated research must incorporate modelling that accurately simulate these compounding effects.

2. A Complex, Multi-Stressed system: The Subarnarekha River Basin

A. Hydro-Geographic and Socioeconomic Background

The Chota Nagpur plateau, Close to Ranchi, Jharkhand (near Nagri village), is the source of the Subarna Rekha River, a vital rain-fed system in Eastern India [5]. Before emptying into the Bay of Bengal, it travels 395 kilometers. The interstate nature of the basin, which spans 19,296 km^{2}and includes important drainage areas in Jharkhand (68.4% of the catchment), Odisha (16.1%), and West Bengal (15.5%), makes it strategically important.

State	Catchment Area(km2)	Percentage
Jharkhand	13,193	68.4
Orissa	3,114	16.1
West Bengal	2,989	15.5
Total	19,296	100

The South-West monsoon is inextricably tied to the river’s flow, resulting in extremely seasonal and erratic flow patterns. The significant temporal variability necessitates focusing on flow extremes rather than just annual means for effective management. The 1964 settlement among the riparian states (the Bihar, Orissa and West Bengal) is an example of how complicated political negotiations were required in the past to share the river’s water resources. These current interstate water allocation procedures are anticipated to be severely strained in the future due to the anticipated climate driven increases in flow variability, especially between monsoon peaks and dry season lows.

B. Environment Degradation Footprint and Infrastructure

Major water infrastructure, including the Getalsud Dam completed in 1971, is situated within the Subarnarekha River basin, approximately 50 kilometers from the river's source [1].The river is a component of the Subarnarekha Multi-Purpose (SMP) project, which includes numerous dams and barrages and is provides water for industrial and municipal usage [1]. These facilities, while important for hydropower and water security, disrupt natural flow regimes, alter river morphology, and impact downstream ecological health [10]. Beyond changes in flow, mining and industrialization are causing serious environmental damage in the basin. For example, the Hindustan Copper Limited (HCL) mines are well-known in the vicinity of Ghatshila [1]. Water quality has significantly declined as a result of mining operation and anthropogenic stresses from industrial and household effluents [12]. Research has shown heavy metals like arsenic, lead and chromium are present in the vicinity of mining zones. These metals have been linked to a 40% decrease in local fish diversity as well as moderate to severe organic pollution (Biochemical Oxygen Demand or BOD, measured up to 5.7 mg/L) [15].

Water quality results are directly impacted by hydrological changes. Lower dilution capability for these contaminants is caused by decreased volumetric flow rates during crucial dry seasons, which are exacerbated by water abstraction [13]. The calculation of minimum environmental flows required to guarantee adequate pollutant assimilation and maintain the ecological integrity endangered by these persistent anthropogenic pressures must therefore be profoundly informed by research on flow quantity.

3. Measuring Anthropogenic Factors: LULC Change's Dominance

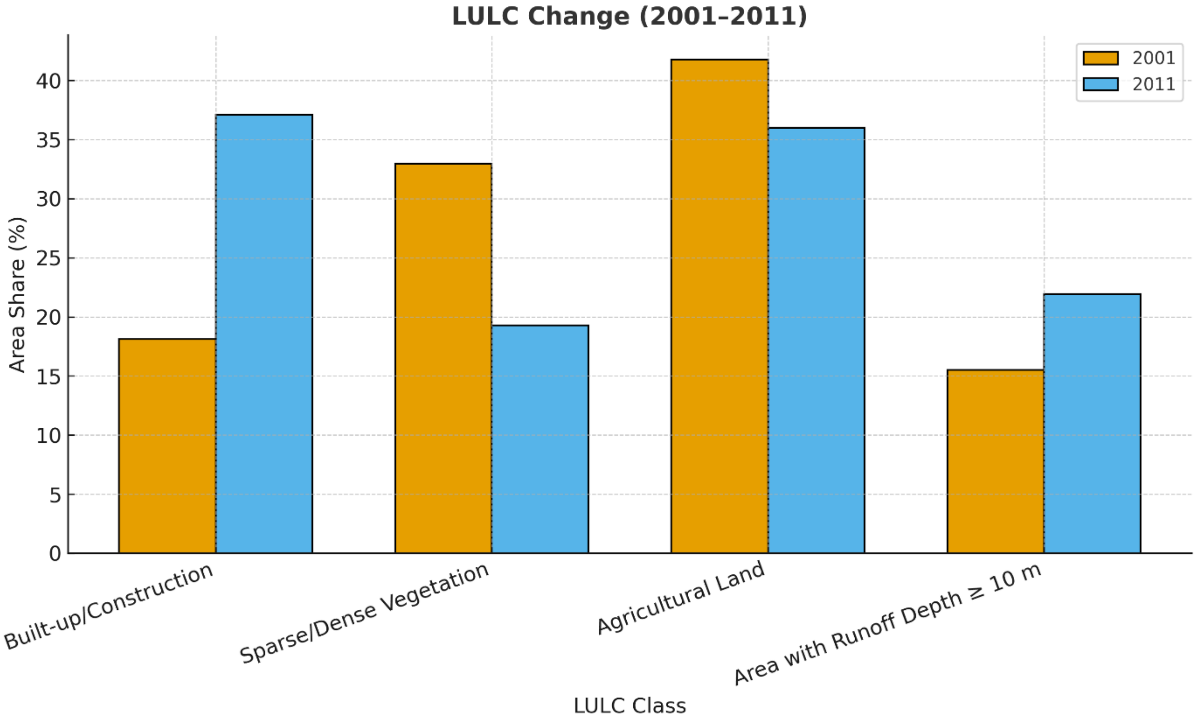
A. Empirical Study of Quick Catchment Change

Rapid land use alteration in the catchment area has the most direct and significant effect on the hydrological character of the Subarnarekha. Urbanization is growing at an alarming rate, according to a comparison research conducted between 2001 and 2011[1]. The percentage of the catchment area that was considered built-up almost double during this decade rising from 18.13% in 2001 to 37.08% in 2011 [1]. Natural cover was directly impacted by this expansion: agricultural land fell from 41.76% to 35.99% while sparse and dense vegetation dropped from 32.94% to 19.28%.

An obvious physical explanation for the increasing susceptibility to flooding is this aggressive urbanization. The region with high runoff depth (≥ 10 m) expanded from 15.50% to 21.92% as a result of the quick development of the impermeable surfaces [1]. At the same time, the micro-watersheds mean runoff level increased from 0.12 m to 0.14 m [1]. Further building presents a major and increasing flood risk since the built-up percentage of the upper watershed (currently 37%) greatly exceeds the accepted 3% to 5% threshold beyond which urbanization is known to exert a statistically significant influence on stream flow regimes [2].

Table 2: Observed Land Use/Land Cover Change and Hydrological Impact in the Subarnarekha Upper Watershed (2001–2011) [1].

LULC Class	Area Share (2001)	Area Share (2011)	Net Change (%)	Hydrological Consequence
Built-up/Construction	18.13%	37.08%	+18.95%	Severe increase in Surface Runoff; Exceeds statistical significance threshold.
Sparse/Dense Vegetation	32.94%	19.28%	-13.66%	Significant reduction in Evapotranspiration and Infiltration Capacity.
Agricultural Land	41.76 %	35.99%	-5.77%	Reduced water retention capacity; Contributes to increased runoff intensity.
Area with Runoff Depth ≥ 10 m	15.50%	21.92%	+6.42%	Direct quantification of increased flood vulnerability.



B. **Differential Hydrological Impacts of LULC Components**

It is necessary to break down the overall change in flow discharge into the distinct effects of each of its component LULC drivers: By lowering Evapotranspiration (ET) and the Leaf Area Index (LAI), the loss of forest cover has a direct on the energy and water balance. Trees stop sediment flow and greatly retain water [4]. Less water is released back into the atmosphere and more water is quickly transformed into surface runoff when forests are replaced with other land cover types, especially agriculture or populated areas [18]. The strong, non-linear impact of deforestation on stream production is demonstrated by literature showing that even small losses in canopy cover (e.g. 10%) can result in increase in annual water yield ranging from 20 mm to 40 mm [4]. Regional atmospheric effects are also significantly impacted by changes in flora, as in the case of the Indochina Peninsula [19].

Concurrently, infiltration is significantly impacted by the shift of agricultural land to building sites. Surface runoff increases dramatically as a result of this change, but deep percolation and lateral flow decrease in tandem [20]. Farmers may suffer financial losses as a result of land loss, but downstream stakeholders may gain from the temporary storage of flood water [22]. The region’s diminishing ground water trends are a direct result of this effect’s inhibition aquifer recharge [21]. The natural storage capacity of the watershed is severally degraded as a result.

Additionally, research using hydrological modeling verifies that the effects of LULC change are strongly scale-dependent. Studies at the sub-basin or micro-watershed level show that surface runoff and water yield can rise significantly (up to 13.6% and 8% respectively) in localized areas undergoing heavy urban expansion, but basic level studies may indicate little change [23]. Therefore, in order to effective mimic this spatial heterogeneity and connect particular land use decisions to localized changes in flood risk measures, the research needs employ a physically semi-distributed model subdivided by homogeneous hydrological Response Units (HRUs).

4. Modeling Framework: Climate Projection, Uncertainty and SWAT

A. The SWAT Model's Robustness and Applicability

To obtain the necessary degree of quantification, the proposed study will make use of the **Soil and Water Assessment Tool (SWAT)**, which is coupled with Geographic Information System (GIS) technology [1]. Known for its capacity to forecast the long-term effects of different land management techniques on water and sediment yields, SWAT is a basin-scale, physically based model created especially for complex hydrological systems [1].

The Chotanagpur plateau's diverse terrain and quick LULC fluctuations are well reflected by SWAT's design, which divides the watershed into sub-basins that are then further classified into HRUs based on uniform land use, soil and management features [1]. Successful regional applications, such as the simulation of surface runoff in the upper Subarnarekha and other tropical river basins in Eastern India, have already demonstrated its usefulness. GIS technology is essential to this procedure since it provides the spatial input layers required to set up the Arc-SWAT model [1].

B. Advanced Methods for Quantifying Uncertainty and Calibration

To guarantee the accuracy of flow simulations, the Arc-SWAT model must be rigorously calibrated and validated. Advance methods for uncertainty analysis and parameter optimization must be used in the process. The established framework for addressing these issues is the SWAT-Calibration and Uncertainty Programs (SWAT-CUP), specifically using the Sequential Uncertainty Fitting Algorithm (SUFI-2) [2]. SUFI-2 is robust for quantifying the combined uncertainty of model structure, inputs and parameters through metrics like the P-factor and R-factor [24]. Supporting computational tools like MATLAB and SPSS enable the analysis of historical time-series data related to rainfall, temperature and water discharge patterns, allowing trends and statistical validation of model outputs [26].

Modern data sources must be incorporated into the validation process because many Indian River Basins, including portions of the Subarnarekha, are poorly gauged. The model can be calibrated and validated against regionally dispersed hydrological components by utilizing remote sensing observables, such as satellite-derived actual evapotranspiration (ETa) or Total Water Storage Change (TWSC) [30]. This process has been very successful in obtaining high model performance metrics ($R^2 >$ 0.9 and NSE > 0.8), thereby lowering the uncertainty associated with limited conventional stream flow records. It entails performing Global Sensitivity Analysis (GSA) to identify influential parameters using tools like SUFI-2 [31].

C. Requirements for Future Climate Projection and GCM Downscaling

Reliable future climate forcing data is necessary for accurate flow predictions in 2050 [1]. Despite their sophistication, Global Climate Models (GCMs) are not appropriate for basin-scale SWAT inputs since they operate at coarse geographic resolutions [32]. As a result, the methodology requires that certain GCMs' climate data be downscaled [1]. The downscaling process improves resolution, allowing the model to capture important local-scale climate variability, especially the spatially non-uniform changes in Indian monsoon precipitation [33]. Recent methodological advancements include statistical downscaling using sophisticated machine learning techniques, like Convolutional Long Short-Term Memory (ConvLSTM) networks [32]. These approaches are becoming more and more popular because they have better representation of extreme events and superior predictive capabilities for regional rainfall when compared to traditional methods.

Additionally, by carefully choosing GCM ensembles, such as those from the CMIP6 framework, using criteria like compromise programming (CP) to guarantee that the model selected best represent pertinent climatic variables, stream flow projection reliability is improved [34]. By combining these highly resolved and bias-corrected climate projections, the final SWAT simulation can offer a confident projection of future volumetric flow rate changes by 2050.

5. Combining the Effects of Climate Change with the Associated Hydrological Reaction

A. The Theory of Extreme Variability

The idea that the Subarnarekha basin's water availability will become more volatile over time due to climate change is supported by the linked framework. According to climate forecast, severe flows will be significantly amplified by 2030-2080, monsoon flow might increase by 100%-200% [36]. The anticipated rise in precipitation intensity and the quick movement of water as a result of widespread LULC alterations are directly responsible for this increase in magnitude.

On the other hand, increased water stress during the dry season is caused by the same factors. While the loss of forest cover and natural infiltration regions due to building significantly affects the replenishment of groundwater stocks, higher air temperatures and increased evapotranspiration will result in greater water losses [18]. Water is rapidly lost from system due to the quick conversion of rainfall to surface runoff, which prevents deep percolation and jeopardizes the base flow contribution to the river during non-monsoon months. As a result, the hydrological response is one of the sharply enhanced extremes: within the same yearly cycle, longer more severe droughts (low 5th percentile flows) are followed by more powerful, devastating floods (high 95th percentile flows).

B. Outlining the "Business-as-usual" Situation for Intervention in Policy

Establishing a quantifiable risk baseline is the goal of simulating the "business-as-usual" (BAU) scenario for 2050 [1]. This scenario is predicted on the persistence of observable trends, such as the ongoing exponential growth in built-up area and the corresponding loss of forest and agricultural land, as well as the present climate forcing trajectories combined with the sustained, high rate of LULC conversion [37].

The BAU simulation's ability to behave as a counterfactual is its main advantage. The calculated risks under BAU must be contrasted with alternative, policy-driven scenarios, such one that incorporates stringent Sustainable Land Management (SLM) techniques or Nature Based Solutions (NbS), in order to establish truly adaptive water management policies [37]. BAU forecast have shown dramatic results in similar urbanizing Indian river basins, such as a 105% increase in flood depth under catastrophic by 2100 [39]. A quantitative comparison, such as demonstrating how an SLM scenario could lower that anticipated surge by 44%, provides the concrete proof needed to support infrastructure and regulatory expenditure [39]. Thus, the BAU simulation converts scientific forecasts into a clear directive for quick policy response [37].

1. Policy Suggestions and Adaptive Water Management

A. The Subarnarekha Context of Integrated Water Resources Management (IWRM)

The Integrated Water Resource Management (IWRM) frameworks, which use the natural hydrographic basin as the logical unit for administration, must be adopted in order to manage the Subarnarekha River [40]. The Subarnarekha's distinct, multi-stressed environment necessitates that the IWRM approach give priority to:

1. **Controlling Flow Extremes:** To control the dangers of both the high-flow (flood) and low-flow (drought), proactive steps must be taken. In order to balance municipal supply and flood control ca-

pacity while maintain the minimal environmental flows required for ecological health, it is vital to optimize the operation of existing infrastructure, such as the Getalsud Dam [10].

2. **LULC-Sensitive Planning:** in order to prevent the growth of impervious surfaces and stop riverbank encroachment, which has already impacted more than 32% of the riverbanks in urban areas, watershed management must clearly link urbanization policies to hydrological consequences by controlling land use in flood-sensitive sub-basins [15].
3. **Pollution and Quality Control:** The IWRM plan must strictly implement pollution control programs, integrating them with land use planning to manage effluent and non-point source pollutants within the watershed, due to the ecological dangers posed by mining and industrial contaminants [43].

B. Strategies for Mitigation: Assessing Nature-Based Solutions (NbS)

A very successful intervention technique to reduce the flood risk increased by the high rate of urbanization in the basin is provided by Nature-Based Solutions (NbS) [44]. These techniques improve the urban landscape by utilizing natural processes [44]. It is critical that NbS be implemented right away in the metropolitan areas (Ranchi, Jamshedpur) and upper catchment. This comprises:

- **Restoration and Protection of Pervious Surfaces:** It is essential to restore wetlands, preserve current forest cover and increase urban green areas [44]. Often referred to as natural sponges, wetlands improve water absorption, lengthen hydraulic residence times and successfully lower downstream peak flows [45].
- **Soil Conservation:** By reducing sediment yield and improving infiltration in high-priority areas (16.63% of the total study area), as determined by geospatial vulnerability mapping, soil and water conservation measures can be implemented. This will increase ground water recharge and contribute to robust base flow during non-monsoon periods [46].

  NbS is a key element of adaptive water management in the Subarnarekha Basin, as modelling studies in comparable situations show that including such measures can significantly reduce the anticipated rise in flood depth and offer reciprocal benefits for drought mitigation [47].

2. Strategic Research Gaps and Conclusions

A. Conclusion Synthesis

The Subarnarekha River Basin is a crucial system that is experiencing increased hydrological instability because to the combined effects of intensive human LULC conversion and anticipated climate change. The most significant concern is a sharp rise in temporal flow variability, which is typified by prolonged, severe water scarcity during the dry season and more frequent and severe floods during the monsoon. The suggested approach, which is based on the Arc-SWAT model and is backed by GCM downscaling and thorough uncertainty analysis, offers the scientific basis required to measure these coupled stresses and precisely predict the effects of a business-as-usual trajectory toward 2050. In order to restore the basin's natural buffering capacity, the analysis requires that future water policy move away from reactive measures and toward proactive land use planning and the prompt implementation of Nature-Based solutions.

The proposed methodology, centered on the Arc-SWAT model supported by GCM downscaling and rigorous uncertainty analysis, provides the necessary scientific foundation to quantify these coupled stressors and accurately forecast the consequences of a business-as-usual trajectory toward 2050. The analysis mandates that future water policy shift away from reactive measures toward proactive land-use planning and the immediate implementation of Nature-Based Solutions to restore the basin's natural buffering capacity.

B. Research Gaps and Prospects for Strategy

To further strengthen the scientific basis for resilient management, future research should address the following strategic gaps:

1. **Dynamic Socio-Hydrological Modeling:** In order to simulate the feedback loop between human behavioral responses (such as altered land use adoption by farmers or city planners) and climate change impacts (such as increased flooding), future models should incorporate agent-based modules [48]. Adaptive actions, such expanding conservation acreage by up to 60%, can dramatically reduce runoff, according to these models [48]. This will produce LULC scenarios for hydrological projection that are more adaptable and realistic.
2. **Integrated Water Quality Modeling:** To predict the fate and transport of important contaminants (heavy metals, sediment loads) inside the Subarnarekha, the research should extend the SWAT framework. In order to forecast how decreased baseflow in 2050 will affect pollutant concentration and the ensuing hazards to human health and the environment, this integration is vital. It also provides vital information for controlling mining and industrial operations.
3. **Hydro-Economic Valuation:** Future research should conduct a thorough economic analysis that directly quantifies the estimated damages (such as flood costs and drought losses) under the BAU scenario in comparison to the economic returns and mitigation benefits produced by investing in particular NbS strategies and enforcing regulations. In order to secure political support for sustainable resource control, this financial analysis is essential.

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