

Chapter 3

Optimal Management of Potential Water and Sediment Yield from Urban Hilly Watershed



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Abstract The sustainable ecological management of soil and water yields from hilly watersheds of an urban area is a real challenge from the perspective of economic and structural feasibility. It is of key importance for future city planning to implement ecological management practices (EMPs) optimally in urban hilly watersheds incorporating future urban growth. To achieve this, here, the Revised OPTimal EMP Model with Linear Programming for Single Ownership (R-OPTEMP-LS) is applied to manage the water and sediment yield calculated concerning a future LULC scenario of a hilly urban watershed of Guwahati city, India. The future LULC of the study area has been derived by using the ASEA (Assessment of Settlements in Eco-sensitive Area) model. The model parameters were input from the “Master Plan for Guwahati Metropolitan Area – 2025”. It is found that in 2025, although the sediment yield from the watershed can be managed by executing the optimal combinations of EMPs, the peak runoff will be manageable only if the rainwater harvesting system will be strictly installed along with the EMPs. The model result says that for a 36.73% increase in the urban settlement in the hilly watershed from 2015 to 2025, there is a 33.4% increase in the total cost of EMPs. The high economic investment to control the adverse consequences of urban development in the hilly areas of Guwahati city emphasizes the need for strict conservation of those ecologically sensitive areas.

Keywords Projected urban settlement · ASEA · Soil loss · RUSLE · Peak runoff · Rational method · R-OPTEMP-LS

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3.1 Introduction

The increased imperviousness not only magnifies the amount of runoff volume but also lowers the time of concentration, which thus produces flash floods (Ng and Marsalek 1989; Viessman et al. 1989; Flinker 2010). Due to the sedimentation in the drainage channels, the soil erosion manifests the urban flash floods manifold (Kondoh and Nishiyama 2000; Ozacar 2013). Therefore, for the ease of hydrological investigation and to achieve a sustainable as well as an environment-friendly solution for hazards like urban flood and soil erosion, watershed management practices are essential (Sarma et al. 2015; Poonia et al. 2021). Urban development must therefore be designed in such a manner that it can minimize adverse effects along with the achievement of the developmental objectives (Mukheibir 2008; Goyal et al. 2018).

Different land covers respond differently to the hydrological hazards with diverse efficiencies of their soil erosion and runoff control (Poff et al. 2006; Goyal and Ojha 2012; Das et al. 2020). This makes the land use-based urban management strategies well-accepted, drawing the continuous attention of researchers from different disciplines (Tong and Chen 2002; Stutter and Lumsdon 2008; Goyal and Ojha 2010). Ecological management practices or EMPs, introduced by Sarma (2011), are considered as appropriate and competent urban watershed management practices if implemented appropriately (Patowary et al. 2019). EMPs are used to define the structural and vegetative means including cultivation or plantation of various shrubs, grass, or trees, contour terracing, retention and detention ponds, rainwater harvesting systems, vegetative buffer zone, stone or boulder pitching, retaining wall, etc. These measures are not only used for controlling soil erosion and runoff but also for controlling water pollution and carbon sequestration (Sarma et al. 2015). However, the expenditure, effectiveness, and suitability of EMPs are generally different for different places based on the condition of the proposed construction area. It claims the use of optimization techniques, which were successfully used in the past to answer the multi-objective environmental or water resources along with the land allocation problems (Chang et al. 1995; Gabriel et al. 2006; Hsieh and Yang 2007; Karterakis et al. 2007; Sadeghi et al. 2009). Sarma et al. (2015) introduced OPTEMP-LS (OPTimal EMP Model with Linear Programming for Single Ownership) for the optimum allocation of EMPs and performed a sensitivity analysis to determine how the project cost is sensitive to the various model parameters such as rainfall intensity, soil erodibility factor, runoff factor, etc. Patowary et al. (2019) revised the OPTEMP-LS by including the hill cut factor to determine the optimal combination of EMPs more accurately, based on GIS-based urban settlement estimation. The hill cut factor assesses the steep hill cut area (caused due to the residential development) that is rarely identifiable in ortho-rectified satellite images (Patowary and Sarma 2018). Again, the dynamic behaviour of the effect of urbanization always highlights the necessity of potential projection of various hydrological hazards to plan the management scheme accordingly. Despite the availability of several studies focusing on the best possible land cover combination for minimizing

the undesirable impacts of urban development, this study uses the EMPs in urban hilly watersheds considering the potential urban development there. Therefore, the basic aim of this study is to apply the revised OPTEMP-LS with reference to the future hydrologic data derived by using potential urban settlement. The study has been carried out concerning an urban hilly watershed of Guwahati city, the capital of Assam. The future urban settlement data for the study watershed has been taken from Patowary and Sarma (2020), estimated by using the ASEA model. With the application of these data, the future hydrological parameters like peak runoff and sediment yield have been calculated, and finally, the R-OPTEMP-LS has been run based on these data.

3.2 Materials and Method

3.2.1 Study Area

The area selected in this study is an urban watershed of a hill of Guwahati city, the most developed city in the northeastern part of India. The city is witnessing a high urban expansion turning its eco-sensitive hilly regions into urban areas (Sarma et al. 2013, 2015). In every rainy season, the high amount of water and sediments coming from the urban-induced hilly areas are causing drainage congestion leading to devastating urban flash floods (Patowary et al. 2019). As projected by Patowary and Sarma (2020), the urban settlement in the hilly area is going to be increased by 11.12% from 2011 to 2025. This gives an idea of the worst condition of urban flash floods in Guwahati city. The location of the study area (watershed) in Japorigog hill, which is a part of the core area of Guwahati city, is shown in Fig. 3.1. Watershed has been delineated by using ArcSWAT with a Shuttle Radar Topography Mission (SRTM) DEM (digital elevation model) of a resolution of 1 arcsecond. The slope of the study area changes from 0° to 32.9° (with an average slope of 14.17°), and the elevation changes from 59 to 177 m. The total area of the hilly watershed is 74 ha, of which 30.8% was the urban settlement in 2015 (Patowary et al. 2019).

3.2.2 Estimation of Future Urban Settlement

Patowary and Sarma (2020) projected the urban settlement in the entire 15 hills of Guwahati city by applying the ASEA model. It is an indirect urban settlement assessment model, which uses the socio-economic, demographic, and geographical conditions of an area to estimate the urban settlement. The future data of the socio-economic, geographical, and demographic parameters of the model were generated concerning GMDA (2009). In this study, the projected LULC data of the study area for the year 2025 has been prepared by clipping the projected LULC map of the Japorigog hill of Guwahati city in ArcGIS 10.4.1. Figure 3.2 depicts the LULC map

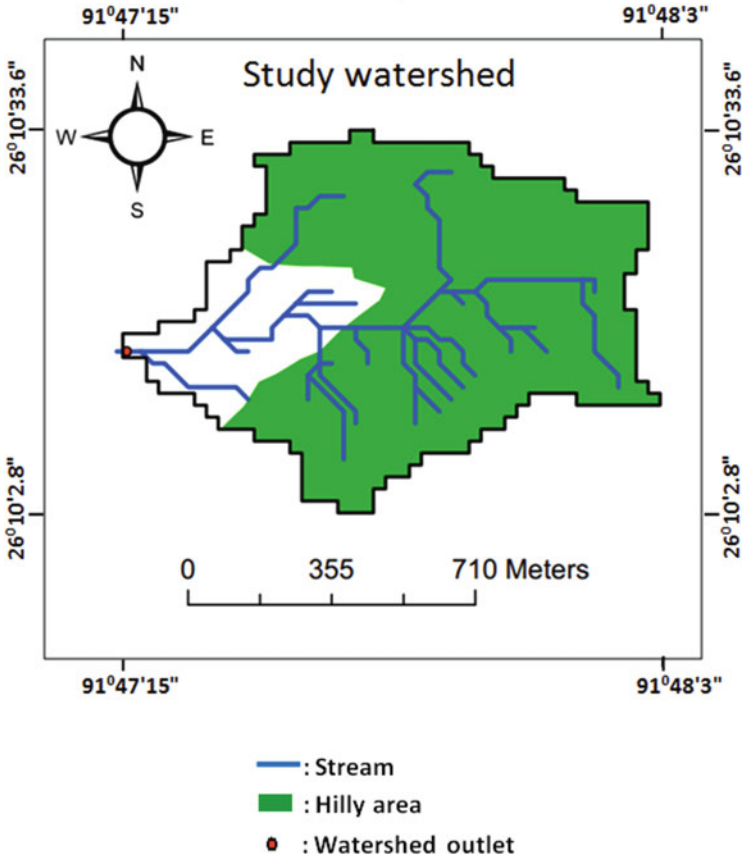


Fig. 3.1 Study area

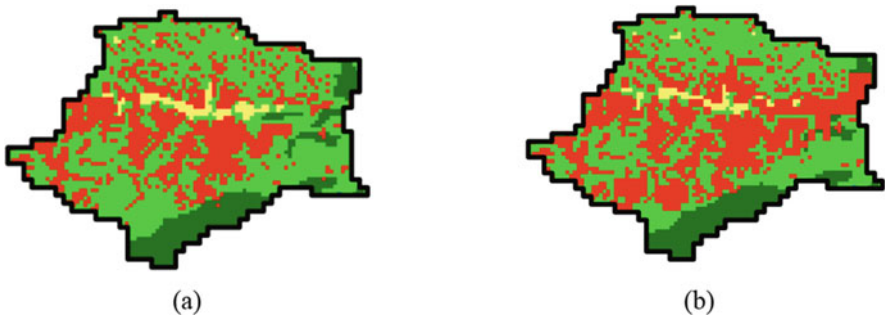


Fig. 3.2 LULC maps of the watershed: (a) 2015 and (b) 2025 (light green, scrubland; dark green, forest; yellow, bare land; red, urban settlement)

of the study area in 2025. For comparison, the LULC map for the year 2015 (extracted from the LISS IV satellite image of 4 December 2015) has also been presented. It is found that from 2015 to 2025, urban settlements in the study area increase by 36.73%.

3.2.3 *The Optimal Combination of EMPs in the Future*

3.2.3.1 **The R-OPTEMP-LS**

This R-OPTEMP-LS (Patowary et al. 2019) is a linear programming-based optimization model. The objective function of the R-OPTEMP-LS is defined to minimize the sum of the costs of EMPs, essential to bring the yearly values of sediment yield and peak runoff within permissible limits. This is controlled by various conditions like existing LULC type, soil type, slope, simplicity of maintenance, and availability of land. Water and sediment yield constraints are presented with the help of rational method (Kuichling 1889) and GIS-based RUSLE (revised universal soil loss equation; Renard et al. 1991), respectively. Here, the complete watershed has been considered under a solo proprietor (in the form of private developers, society, government, etc.). The detail of the R-OPTEMP-LS has been given in Fig. 3.3.

3.2.3.2 **EMP Selection**

Based on the accessibility and execution convenience, the EMP selection has been done for the year 2025. For the settlements in the plain area of the watershed, the optimal values (area) of the selected EMPs—grass, garden (vegetables, shrubs, as well as bushy vegetation), forest, and detention pond (depth = 1.5 m, Sarma et al. 2015)—are represented by Xp_1 , Xp_2 , Xp_3 , Xp_4 , correspondingly. The similar EMPs for the hilly portion are symbolized by Xh_1 , Xh_2 , Xh_3 , Xh_4 , respectively. Again, for the near-vertical steep hill cuts, two EMPs—grass/creepers and retaining wall with random rubble masonry—have been selected, the optimal values of which are denoted by Yh_1 and Yh_2 , respectively.

The cover management factors, the runoff coefficients, and the costs per unit area of EMPs have been used from the past literature (Sarma et al. 2005; San Diego County 2003; ODOT Highway Division 2014; Wischmeier and Smith 1961; Gelagay and Minale 2016; Patowary and Sarma 2018; Patowary et al. 2019). These studies estimated the unit costs by using the market rates of the year 2012–2013. It is worth mentioning that, although for the theoretical application purpose, here, unit costs have been taken from the past literature, it is essential to use the latest available costs for the real field application of the model.

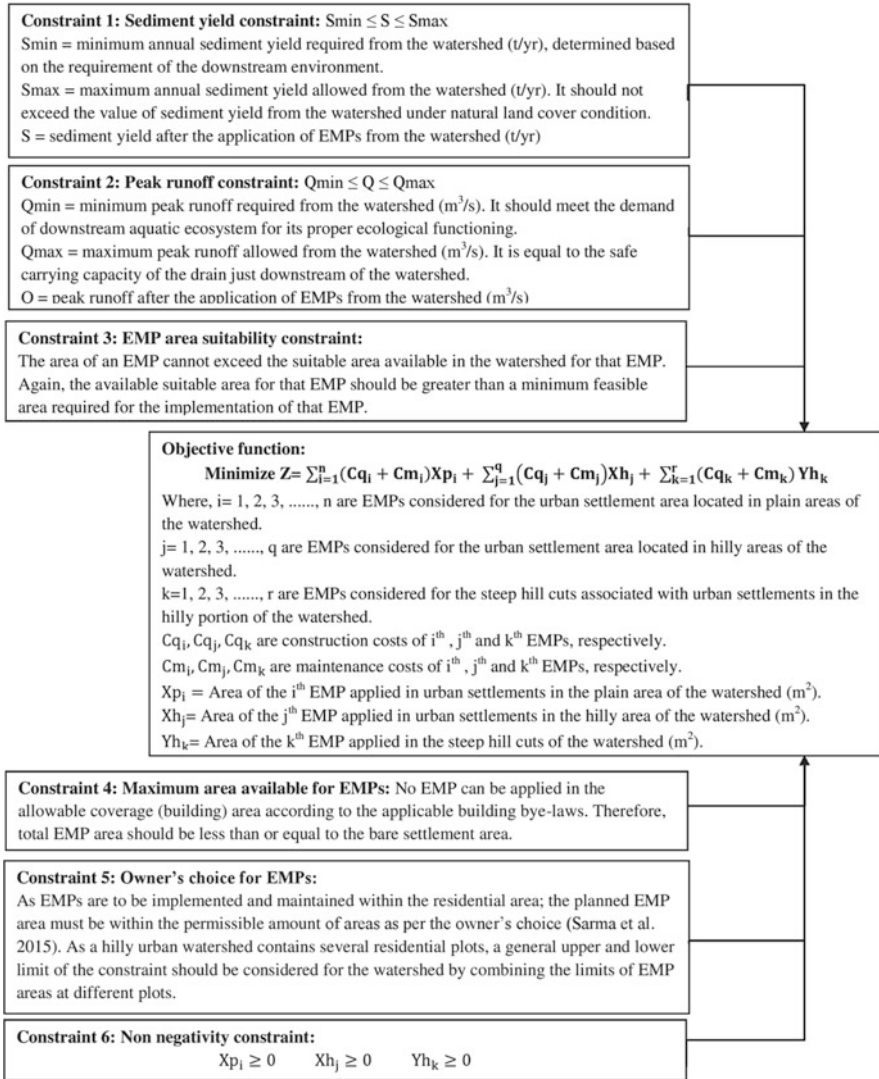


Fig. 3.3 The detail of the R-OPTTEMP-LS

3.2.3.3 Constraints

1. Constraint for sediment yield and peak runoff: As given in Fig. 3.3, the maximum and minimum limits of sediment yield and peak runoff have been calculated and obtained as follows:

$$S_{\min} = 0, S_{\max} = S_{\text{natural}} = 2608.79 \text{ t/year},$$

$$Q_{\min} = Q_{\text{natural}} = 2.979 \text{ cumec}, Q_{\max} = Q_{\text{drain}} = 4 \text{ cumec}$$

2. Constraint for suitability of EMP area: The superimposition of the soil map (collected from Assam Remote Sensing Application Centre, Guwahati), DEM, and slope map of the study area in ArcGIS gives that all the chosen EMPs are applicable to the plain bare settlement area, but to the steep hill cut area, only the grass and retaining wall are applicable.
3. Maximum area available for EMP:

The total EMP area \leq bare settlement area.

As given in Patowary et al. (2019), this constraint is obtained as:

$$\sum_{i=1}^4 X_{p_i} \leq 0.4 \times U_{\text{sp}} \quad (3.1)$$

$$\sum_{j=1}^4 X_{h_j} \leq 0.4 \times U_{\text{sp}} \quad (3.2)$$

$$\sum_{k=1}^2 Y_{h_k} \leq 0.6 \times \frac{\sin \theta}{\sin(\beta - \theta)} \times U_{\text{sh}} \quad (3.3)$$

where the built-up area in the plain watershed area is derived from the LULC map of the year 2025, $U_{\text{sp}} = 69,188 \text{ m}^2$.

Similarly, settlement in the hilly watershed area, $U_{\text{sh}} = 218,148 \text{ m}^2$.

The average hill cut angle is $\beta = 70^\circ$ (Patowary et al. 2019).

The natural slope (average) of the hilly watershed area is $\theta = 14.17^\circ$ (derived from slope map in ArcGIS).

Again, as given in Patowary et al. (2019), owners' choices have been considered hypothetically.

3.3 Results and Discussions

The "Linear Model Solver Tool" of "Microsoft Excel" application has been used to solve the optimization problem. It is found that the execution of the chosen EMPs makes the sediment yield manageable within allowable limits. However, it is not feasible to keep the peak runoff from the watershed within the highest allowable limit due to the projected increase in urban settlements in 2025. This is because 60% of this increased urban settlement contributes only imperviousness producing a high

Table 3.1 Costs of EMP implementation obtained from R-OPTEMP-LS model

	2015 (Patowary et al. 2019)	2025
Cost ($\times 10^7$ Rs)	Total = 10.24	Total = 13.67
	Plain = 0.85	Plain = 0.85
	Hill = 1.97	Hill = 2.69
	Steep hill cut = 7.42	Steep hill cut = 10.13

Table 3.2 Comparison of sediment and water yield for the years 2015 and 2025

		Sediment yield (tonnes/year)	Peak runoff (cumec)
2025	Without EMP	41,267.98	4.75
	With EMP	2602.15	3.85
2015 (Patowary et al. 2019)	Without EMP	34,020.77	4.38
	With EMP	2602.15	4.00
	Natural land cover condition (pre-urbanized)	2608.79	2.99

amount of runoff. The EMPs implemented in the remaining 40% area of urban settlement (bare) are not sufficient to bring the peak runoff within the maximum allowable limit. Sarma et al. (2015) mentioned that the installation of the rainwater harvesting (RWH) system along with the considered EMPs is a good alternative to bring the peak discharge within the permissible limits. By adopting the rooftop rainwater harvesting, the runoff coefficient of the built-up area is becoming possible to lower by 20% in Guwahati city (Sarma et al. 2006). From the last few years, GMDA is giving utmost importance to the adoption of the rainwater harvesting system, and it is now made compulsory in building bye-laws of the city. Therefore, it has been considered that till 2025, RWH schemes will be strictly implemented in Guwahati city, and consequently, in 2025, the runoff coefficient of the impervious area has been expected to reduce by 20%. Under this consideration, a feasible solution is obtained to bring the peak discharge and soil loss within allowable limits in 2025. With the consideration of all the constraints, it is found that for a 36.73% increase in the settlement of hilly watershed areas from 2015 to 2025, there is a 33.4% increase in the overall expenditure of EMPs to maintain the soil loss and peak runoff in the permissible limits. For the ease of interpretation of the effect of future urban settlements on the management cost of the watershed, the results are also compared with that in Patowary et al. (2019) for the year 2015 (Table 3.1). Again, Table 3.2 presents the sediment yield and peak runoff for various situations. It is observed that after EMP implementation, the sediment yields from the watershed are almost the same with those from the natural land surface scenario, although peak runoff values are not the same. After the implementation of EMPs, the less peak runoff value in 2025 than that in the 2015 LULC scenario indicates that the installation of the RWH system along with the other considered EMPs is quite effective in reducing the peak discharge. Again, due to the implementation of EMPs, there is a more efficient reduction of sediment yield than the peak runoff. It

is due to the fact that the impervious area produced due to the increased urban development yields no sediments but a high amount of water.

3.4 Conclusions

This study presents optimal management of an urban hilly watershed considering the future hydrological alterations to be taken place as a consequence of urban development. The study objective has been achieved with the help of two basic models— (a) ASEA model, which determines the urban settlement in an eco-sensitive hilly area based on various socio-economic, demographic, and geographic factors, and (b) R-OTEMP-LS, an optimization model specially developed for hilly watersheds, which minimizes the cost of a combination of EMPs implemented to bring the sediment and water yields within a sustainable limit. The study has been performed for a hilly urban watershed in the central Guwahati of Northeast India. The future urban settlement data for the study area has been extracted from Patowary and Sarma (2020), who applied the ASEA model to project the urban built-up area in the entire hilly areas of Guwahati city for the year 2025. The LULC data of the study area thus obtained for the year 2025 was used in the R-OTEMP-LS to get the optimal combination of EMPs with a minimum possible cost. The result of the R-OTEMP-LS clearly indicates that the city expansion should be strictly prohibited in the hilly areas of Guwahati city as the ecological management of those urban-induced hilly areas will claim a huge financial investment. It is observed that for a 36.73% increase in the urban coverage in the hilly watershed area from 2015 to 2025, the overall expenditure of EMPs will increase by 33.4%. The knowledge of potential economic investment required to manage the future adverse consequences of urban developmental activities in such eco-sensitive areas can be very useful in efficient and eco-friendly urban planning.

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