

Optimal Ecological Management Practices (EMPs) for Minimizing the Impact of Climate Change and Watershed Degradation Due to Urbanization

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Abstract Massive deforestation induced by unplanned urbanization in the hilly watersheds of Brahmaputra basin, India, has led to ecological imbalance and is gradually transforming this basin into a multi-hazard zone. Removal of green cover is also becoming a matter of global concern, as it can accelerate the adverse impacts of climate change. People coming in search of work generally reside in the hills, as they cannot afford the high cost of land in plains. This has led to deforestation of the hilly area and has resulted in increased surface erosion from the upper catchments. Though sediment and water yield from these degraded watersheds could have been minimized by implementing ecologically sustainable management practices (EMPs), such as grass land, forest land and detention pond, poor economic conditions of the people stands in the way of field implementation. On the other hand, major industries, which can be held responsible for emission of greenhouse gases, can be asked to finance greenery development in these hilly watersheds through implementation of selected EMPs to earn carbon credit for them. To convert this concept into reality, the EMP combination must be selected in such a way that it restricts sediment and water yield from the watershed within the permissible limit and maximizes its carbon sequestration capacity at minimum possible cost. Such optimal planning is a prerequisite for preparing an acceptable logical agreement between Government and private companies. Keeping this in mind, an optimization model was developed and applied to a micro watershed of Guwahati to explore its applicability in actual field. The model developed in this study provides most logical carbon credit negotiation, subject to the availability of reliable value of CO₂ sequestration for different EMPs.

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1 Introduction

Urbanization is a universal phenomenon. The developing countries are experiencing rapid and unplanned urbanization which is transforming forested hilly areas into urban lands. This transformation is resulting in severe environmental impacts, particularly in terms of soil erosion in hills and flash floods in the downstream reaches (Brun and Band, 2000; Kondoh and Nishiyama, 2000; Biggs et al., 2010; Viessman and Lewis, 2008; Misra, 2011). Furthermore, removal of vegetative cover leads to a significant reduction in carbon sink and thus aggravates the impact of climate change (Lal, 2004; Shi et al., 2009; Wang et al., 2011). Such interlinked consequences of haphazard development often render urban hilly watersheds a multi-hazard zone. Development should therefore be planned in such a way that it can minimise climate change vulnerability, while satisfying the developmental goals and thus can enhance economic, social and environmental benefits (Mukheibir, 2008)

Development of urban land surfaces with ecologically sound and sustainable measures can mitigate detrimental consequences that are caused by the conversion of natural areas to urban areas. Such eco-friendly sustainable management practices used for maintaining and enhancing landuses in a natural way can be termed Ecological Management Practices (EMPs). EMPs, like contour terracing, mulching, grass, shrubs, detention/retention pond, buffer zone with vegetation and tree, sediment trap, rainwater harvesting systems, and vegetated waterways can be conveniently used for controlling sediment yield and runoff volume from land surfaces (Wang et al., 2004; Hsieh and Yang, 2007; Kaini et al.; 2012). In addition, rainwater harvesting can be a good EMP for urban systems in view of the climate change impacts and increasing water demand for the growing population (Mukheibir, 2008; Ibrahim, 2009). Again, as vegetation has great potential in sequestering atmospheric CO₂ (Jong et al., 2000; Lasco et al. 2002; Freibauer et al., 2004; Jandl et al., 2007), vegetative EMPs can provide additional benefit by reducing climate change impacts. The carbon sequestration capacity of vegetation depends upon the complex interaction between climate, soil, tree species and management, and chemical composition of the litter as determined by the dominant tree species (Lal, 2005) and thus different vegetation types provide different carbon sequestration potential.

In developing countries, poor economic conditions of the people stand in the way of field implementation of EMPs. Implementation and maintenance costs of EMPs often become unaffordable for the people in lower economic groups and thus sustainability of EMP projects becomes an issue. In such situations, the economic sustainability of an EMP project can be achieved by utilizing the economic value of the implemented EMPs. One way of obtaining financial support for EMPs is to utilize the carbon sequestration potential of vegetative EMPs to earn carbon credit. Industries, which are responsible for green house gas (GHG) emissions, have a moral responsibility of contributing towards enhancing carbon sequestration and thus they need to earn carbon credit. If a hilly residential area can be developed to have maximum carbon sequestration through application of EMPs, then a polluting industry can be asked to implement and maintain such an EMP area to earn carbon credit in proportion to its GHG emission. The EMP combination must be selected in such a way that it restricts sediment and water yield from the watershed within permissible limits and maximizes its carbon sequestration capacity at minimum possible cost. Such optimal planning is a prerequisite for preparing an acceptable logical agreement between Government and private companies.

Real world system problems, involving management of land and water resources, usually become multi-objective, as they need to address conflicting social, economic and environmental issues (Gabriel et al., 2006; Riveira et al., 2008; Han et al., 2011). We formulated a watershed-based multiobjective EMP optimization model, entitled OPTEMP-CSMO (OPTimal EMP model considering Carbon Sequestration with MultiObjective optimization), targeting at carbon sequestration maximization and cost minimization. The model uses two most robust hydrological models, Revised Soil Loss Equation (RUSLE) and Rational method, to address the sediment yield and peak discharge restriction constraints. This paper describes the application of OPTEMP-CSMO model to a microwatershed of Guwahati city, Assam, India. It also analysed the scope of compromising between carbon sequestration and EMP cost for the study area. The model developed in this study provides most logical carbon credit negotiation, subject to the availability of reliable value of CO₂ sequestration for different EMPs.

2 The OPTEMP-CSMO model

In OPTEMP-CSMO, the Laxicographic method of solving multiobjective optimization is considered. In this formulation, two objective functions are ranked as follows:

Rank-1 objective function: Maximization of carbon sequestration of EMPs in the watershed

Rank-2 objective function: Minimization of total cost of EMPs in the watershed

$$\text{Maximize } z_1 = \sum_{i=1}^n CS_i a_i \tag{1}$$

$$\text{Minimize } z_2 = \sum_{i=1}^n (Cc_i + Cm_i) a_i \tag{2}$$

where n =the number of possible EMPs that are considered for the study; m =the number of different land covers in the plot except for the EMPs and coverage area; a_i =the area of the i^{th} EMP in the plot (m^2); $(Cc)_i$ =the capital cost of the i^{th} EMP (INR); $(Cm)_i$ =the maintenance cost of the i^{th} EMP (INR); $(CS)_i$ =the amount of carbon sequestration (tonnes/yr) from the i^{th} EMP in the plot having an area of a_i .

2.1 Constraints

- (i) Sediment yield constraint: Annual sediment yield from the watershed after the installation of EMPs should be greater than or equal to the required minimum sediment yield and less than or equal to the maximum allowable sediment yield. This constraint is addressed by using the Revised Universal Soil Loss Equation (RUSLE).

$$S_{\min} \leq \left[RK(LS) \left\{ \sum_{i=1}^n c_i a_i + \sum_{j=1}^m \left(A_j - \sum_{i=1}^n a_i \right) c_j + CcAc \right\} P \right] \leq S_{\max} \tag{3}$$

where S_{\min} =the minimum sediment yield required from the plot (tonnes/yr); S_{\max} =the maximum sediment yield allowed from the plot (tonnes/yr); A =the area of the plot (m^2); R =the rainfall and runoff erosivity index of the plot (100 ft-tonf-in/acre/hr/yr); K =the soil erodibility factor of the plot (tonnes/acre per unit of R); LS =the LS factor of the plot (dimensionless); C_i =the cover factor for the i^{th} EMP in the plot (dimensionless); A_j =the area of the j^{th} land cover in the plot (m^2); and C_j =the cover factor for the j^{th} land cover in the plot (dimensionless)

- (ii) Peak discharge constraints: Peak discharge from the plot should not exceed the maximum and minimum allowable limit for peak discharge from the watershed after implementation of EMPs. This constraint is addressed by using the Rational method.

$$Q_{\min} \leq \left[\left\{ \sum_{i=1}^n RC_i a_i + \sum_{j=1}^m \left(A_j - \sum_{i=1}^n a_i \right) RC_j + RcAc \right\} A \right] IA \leq Q_{\max} \tag{4}$$

where Q_{\max} =the maximum allowable peak rate of runoff from the plot (cumec); Q_{\min} =the minimum allowable peak rate of runoff at downstream from the plot, (cumec); RC_i =the runoff coefficient for the i^{th} EMP in the plot (dimensionless); RC_j =the runoff coefficient for the j^{th} landcover in the plot (dimensionless); Rc =the runoff coefficient of the coverage area (dimensionless); Ac =the coverage area of the plot (m^2); I =the maximum intensity of rainfall for the time of concentration of the selected design storm for the plot (mm/hr)

- (iii) EMP area suitability constraints: The Area of an EMP in a plot cannot exceed the suitable area available in that plot for that EMP. Also, an EMP is allowed only when a suitable area available for the EMP in that plot is greater than a minimum feasible area required for the implementation of that particular EMP.
- (iv) Suitable EMP area constraint is

$$a_i \leq as_i \tag{5}$$

where $(as)_i$ =the suitable area available for the i^{th} EMP in the plot (m^2).

- (v) Maximum area available for EMPs: No EMP is allowed within the coverage area of the plot, as this area will be used for construction of houses.

Available EMP area constraint is

$$\sum_{i=1}^n a_i \leq AL = A - AC_{\max} \tag{6}$$

where, AL =the total available EMP area in the plot (m^2); and C_{\max} =the maximum coverage allowed in the plot (%).

- (vi) Owner’s choice for EMPs: The owner of the plot, for various reasons, may have a choice in the EMP selection. The area of an EMP should not go beyond the maximum and minimum area acceptable to the owner for that particular EMP:

$$(a_{\max})_i \geq a_i \geq (a_{\min})_i \tag{7}$$

where, $(a_{\min})_i$ is the minimum area kept for the i^{th} EMP in the plot according to owner’s choice (m^2); and $(a_{\max})_i$ is the maximum area kept for i^{th} EMP in the plot according to owner’s choice (m^2).

- (vii) Non negativity constraint is

$$a_i \geq 0 \tag{8}$$

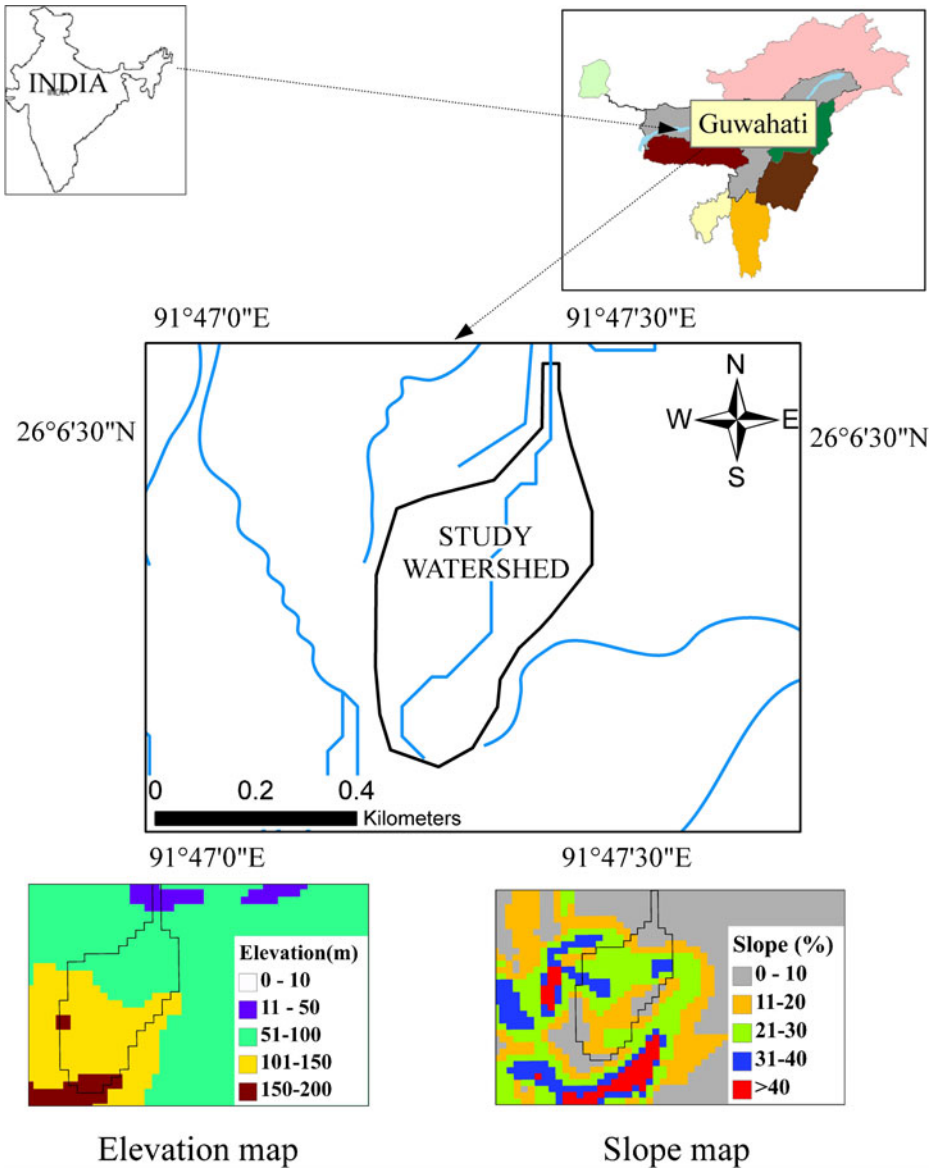


Fig. 1 The Study Watershed

3 Case study

Guwahati, a premier city of Northeast India, is suffering from the severe problem of flash floods due to extensive hill cutting in and around the city. Though sediment and water yield from these degraded watersheds could have been minimized by implementing EMPs, poor economic condition of the people stands in the way of field implementation. Therefore, we considered a micro watershed located near the Games Village area of Guwahati, a site having potential for residential development in its hilly parts (Fig. 1). The ASTER DEM

data was used for delineating the watershed in ArcSWAT. The TIN model for the area was developed by using 20 m contour interval obtained from the Survey of India (SoI) toposheets (1:50000 scale) for developing the slope and elevation map.

3.1 Parameter consideration for OPTEMP-CSMO model

For the OPTEMP-CSMO model, we first determined the allowable limits for sediment yield and peak discharge for the study watershed using RUSLE and the rational method. We considered that when maximum permissible coverage area of the watershed would be used for constructing buildings and the rest for EMPs, the sediment yield from the plot should not exceed the value of sediment yield from the watershed under natural condition, i.e., pre-urbanized condition. However a lower limit of sediment yield (i.e., requirement at the downstream channel) may also exist from a water quality or environment point of view. On the other hand, a minimum amount of water flow is always required to sustain the downstream aquatic ecosystem, thus the value of peak discharge obtained with natural cover was considered as the lower limit of peak discharge (Q_{min}). The maximum allowable peak discharge (Q_{max}) was estimated based on the safe carrying capacity of the drain immediately downstream (Table 1).

3.2 Deriving model parameters for RUSLE

For applying the RUSLE model, the available literature was referred to for obtaining the values of model parameters for the study watershed. The rainfall erodibility factor (R) was chosen by referring to the value obtained by Sarma et al. (2005) in their hydrological study of Guwahati City. For calculation of the Soil Erodibility factor (K) value, the soil map (developed by Assam Remote Sensing Application Centre) was employed. The K value for each soil type was taken from the USLE tables. The average K value for the entire plot was computed by weighting over the entire area. From the slope map, the slope value for each pixel was taken and its corresponding length was considered as the length for that slope. The slope-Length factor for each of the pixels was then determined as referred to by Stone and Hilborn (2000). The LS value for the entire plot was determined by taking the arithmetic average of the LS values computed for each of these pixels. The cover factor for the various land covers (Table 2) was considered, based on the available literature (Renard et al., 1997; Toy et al., 1998; Sarma et al., 2005; Wall et al., 2002). The cover factor for the built-up area was taken as 0, and the cover factor of the barren land was taken as 1. The Practice factor (P factor) was considered equal to 1, as impact of different landuses/EMPs was introduced indirectly by modifying the C factor of USLE.

Table 1 Model Parameters for the Study Watershed

Watershed area (km ²)	Coverage area ^a	R (Sarma et al. 2005)	K	Allowable sediment yield ^b (tonnes/yr)	Allowable peak discharge (cumec) ^c
0.17	60 % of the total area	544	0.17	$S_{max}=2,000$ $S_{min}=0$	$Q_{max}=1.5$ $Q_{min}=0.5$

^a As per the GMDA Building By-Laws (2006), this also includes the area required for infrastructural facilities for that area

^b No requirement of minimum sediment yield from water quality prospective, $S_{min}=0$

^c Flow carrying capacity of a lined canal designed as most economic section based on the existing bed slope (1 %) and average bed width (1.2 m) was taken as Q_{max}

Table 2 EMP Parameters Considered for the Study

EMP name	Carbon sequestration (tonnes/m ²) ^a	RUSLE Cover factor	Rational method Runoff coefficient	Total Cost (INR/m ²) ^b [USD/m ²] ^c	Suitability conditions considered for EMPs			Feasible EMP areas	Owner choice (Hypothetical)
					Suitable soil type	Suitable slope range	Elevation		
Grass	0	0.01	0.2	360 [6.13]	Loam	All	All	Max=AL Min=0	
Shrubs	0.00429	0.01	0.3	290 [4.94]	Loamy	0–60 %	All	Max=AL Min=0	
Forest	0.00092	0.1	0.2	350 [5.96]	All, except rock	0–45 %	< 800 m	Max=AL Min=0	

^a soil carbon sequestration by the EMPs are not considered in this study due to the lack of appropriate data, therefore actual benefits of carbon sequestration will be higher than the value given in Table 2

^b considered based on the prevailing market rate

^c INR 58.76=USD 1

Table 3 EMP Combinations Considering Different Carbon Sequestration Values

Case description	Grass (m ²)	Shrub (m ²)	Forest (m ²)	Peak discharge (cumec)	Sediment yield (tonnes/yr)	CS (tonnes/yr)	Cost (in crores INR) [in millionUSD]
A:CS maximization without considering cost	11,412	34,906	17,453	1.43	1,000	165.81	2.034 [0.346]
B1: Cost minimization considering constraint of CS=PMCS	3,095	34,906	17,447	1.47	2,000	165.80	1.734 [0.295]
B2: Cost minimization considering CS=1 % less than PMCS	4,733	34,906	15,645	1.47	2,000	164.14	1.730 [0.294]
B3: Cost minimization considering CS=5 % less than PMCS	11,287	34,906	8,436	1.47	2,000	157.51	1.714 [0.292]
B4: Cost minimization considering CS=10 % less than PMCS	19,079	34,783	0	1.47	2,000	149.22	1.696 [0.289]
B5: Cost minimization considering CS=11 % less than PMCS	19,466	34,397	0	1.47	2,000	147.56	1.698 [0.289]
B6: Cost minimization considering CS=12 % less than PMCS	19,852	34,010	0	1.47	2,000	145.90	1.701 [0.289]

1 tonnes of CO₂=€18=INR 1,250=USD 28.19 (Jones and Ball, 2010)

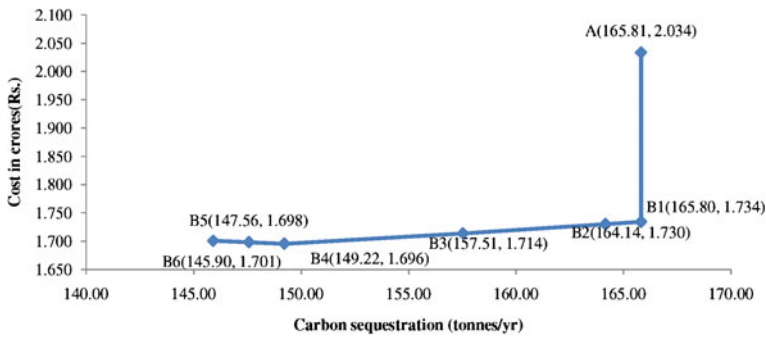


Fig. 2 Variation of Cost with Carbon Sequestration

3.3 Deriving model parameters for Rational method

For applying the rational method, the runoff coefficients for various land covers were considered based on the available literature (Sarma et al. 2005; Iowa Storm Water Management Manual, 2008). The runoff coefficient for the built-up area was taken as 1 and for that of the barren land as 0.5. The runoff coefficient values of other land uses are given in Table 2. As rainwater harvesting is mandatory according to Guwahati Metropolitan Development Authority (GMDA) Building By-Law (2006), we considered the application of rooftop rainwater harvesting system, which can reduce runoff coefficient of built-up area from 1 to 0.8 (Sarma et al., 2006). The intensity of the designed rainfall was obtained as 50 mm/hr by using the intensity duration curve developed by Sarma and Goswami (2004) for the Guwahati City.

4 EMP Consideration

We considered three EMPs, namely grass, shrubs and forest, all having varying characteristics in respect of carbon sequestration, sediment and water conservation and construction and maintenance cost (Table 2). The exact value of carbon sequestration for the considered EMPs in the northeastern region of India are not found in the literature and thus these values were considered as documented by Lasco et al. (2002).

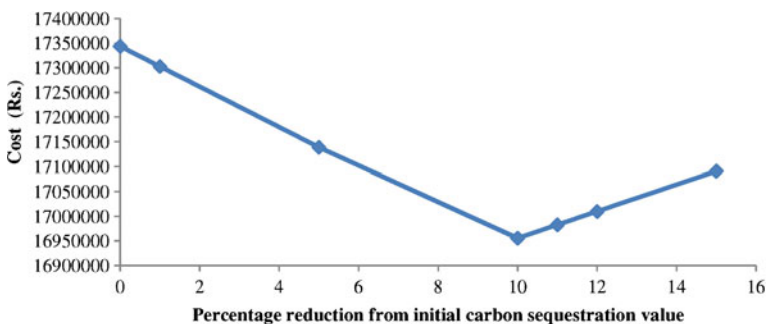


Fig. 3 Changes in Total Cost with Percentage Reduction in Carbon Sequestration

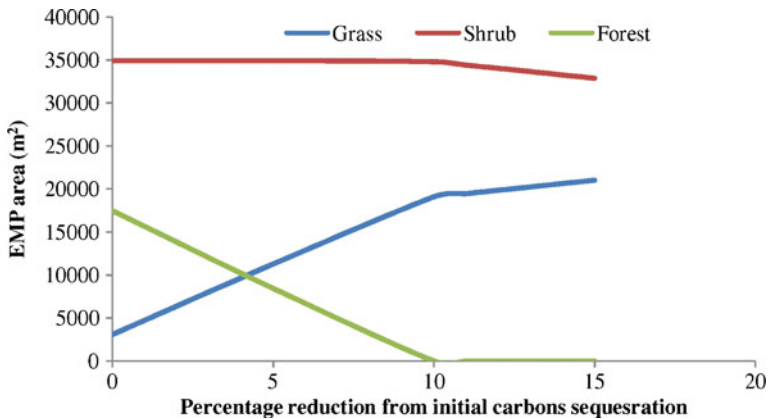


Fig. 4 Changes in EMP Areas with Percentage Reduction in Carbon Sequestration

5 Results and Discussion

The OPTEMP-CSMO model maximizes the carbon sequestration from the area with the considered EMPs subjected to other constraints and we found that the maximum carbon sequestration of 165.81 tonnes/yr can be achieved with the EMP combination costing about INR 2.03 crores (USD 0.345 million), which results with a sediment yield of 1,000 tonnes/yr and peak discharge of 1.43 cumec (Case A of Table 3). This value of carbon sequestration can be regarded as the potential maximum carbon sequestration (PMCS) for the study area subject to the given constraints. In Case A, as cost was not a constraint, it increased the EMP area to maximize the carbon sequestration and doing so the model used higher EMP areas reducing sediment yield up to 1,000 tonnes/yr and peak discharge up to 1.43 cumec, which were much lower than the permissible maximum values. Now, considering carbon sequestration equal to PMCS as an additional constraint, the model was run for minimizing the total cost of EMPs for the plot (Case B1 of Table 3). This gave the optimal EMP cost as INR 1.73 crores (USD 0.294 million) with carbon sequestration value of 165.80 tonnes/yr, sediment yield of 2,000 tonnes/yr and peak discharge 1.47 cumec.

We also analysed the need and scope of compromising between carbon sequestration and cost for the considered EMPs for the study watershed. For purposes of analysis the

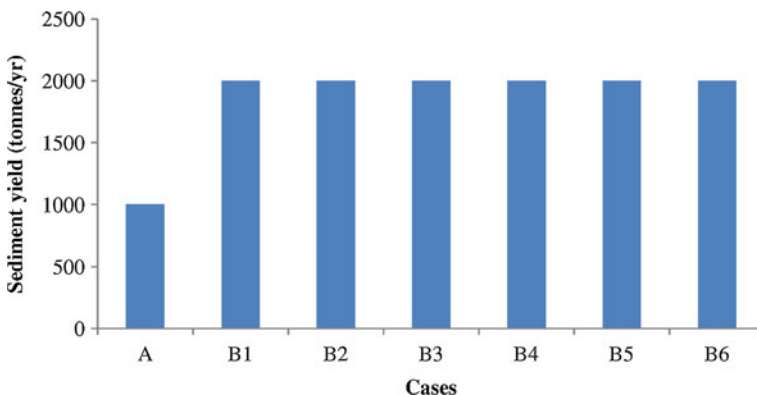


Fig. 5 Sediment Yield in Different Cases

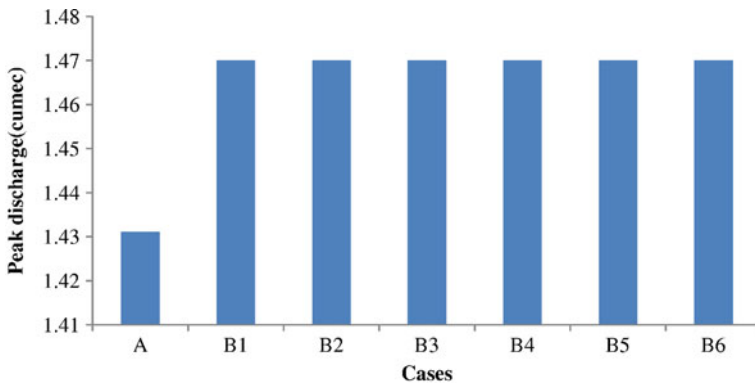


Fig. 6 Peak Discharge in Different Cases

OPTEMP-CSMO model was run by reducing the carbon sequestration value by some percentage of PMCS in a step by step manner and computing the minimum cost achieved for each of these carbon sequestration values. Results obtained are presented in Table 3 (Case B2 to B6). In these scenarios sediment yield and peak discharge were found to be the same as in B1.

Comparison of all these scenarios is presented graphically in Fig. 2 through Fig. 4. In Fig. 2, the variation of total EMP cost with carbon sequestration is presented and the reduction in carbon sequestration reduces the total EMP cost up to a certain limit. However, reduction of the carbon sequestration value beyond 10 % (Fig. 3) did not reduce the cost further, rather it increased the cost, and thus reduction beyond 10 % of the PMCS was not beneficial. This happened because to reduce the CS value beyond 10 % of PMCS, the model made the forest area zero, increased the grass area and decreased the shrub area marginally to satisfy the constraints of sediment and water yield. Figure 4 presents EMP combinations for all these different scenarios and their corresponding sediment yield and peak discharge are represented in Figs. 5 and 6. EMP with the highest carbon sequestration capacity and low cost was found to be consistent for all scenarios. With the percentage decrease in the acceptable carbon sequestration value, EMP areas were adjusted with mutual increase and decrease between grass (comparatively high cost, no carbon sequestration potential) and forest (comparatively medium cost, medium carbon sequestration capacity) (Fig. 7).

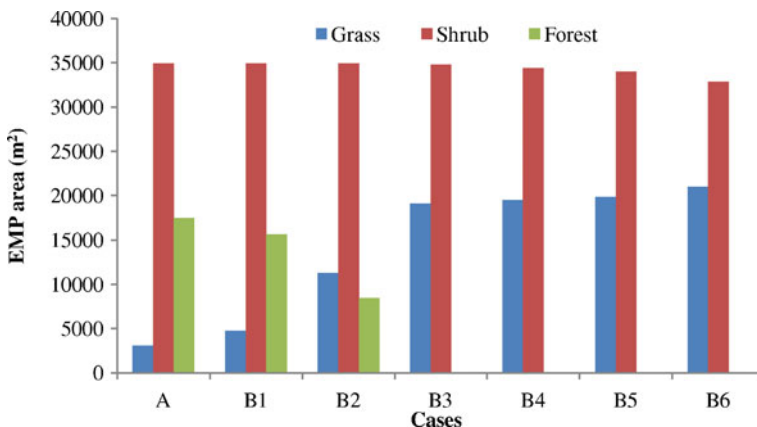


Fig. 7 EMP area in Different Cases

6 Conclusions

Urbanization is a dynamic process and presents both problems and solutions to sustainability challenges (Bao and Fang, 2012). Climate change, in addition to increasing population pressure and land-use changes, poses a major challenge to water resources management (Short et al., 2012). Therefore, sustainable urban development in hilly watersheds is a real challenge, while satisfying conflicting interests that arise from economic, social, administrative and environmental issues- more particularly considering the sustainability of the fragile ecosystem. Judicious implementation of EMPs in hilly urban watersheds can mitigate adverse consequences of urban development in an ecologically sound and sustainable way. Optimal planning considering these aspects can help in achieving an acceptable logical agreement between environment and development. Although many studies on the optimal allocation of different landuses to satisfy conflicting interests of different stockholders are found in the literature, none of these studies has focused on the optimal allocation of EMPs considering their carbon sequestration potential to ensure project sustainability.

This study investigates how to enhance the sustainability of an EMP project by utilizing carbon sequestration potential of vegetative EMPs. The proposed optimal combination of grass, shrub and forest, in addition to satisfying primary constraints of restricting sediment yield and peak discharge within permissible limit, could contribute towards mitigating climate change impacts by maximizing carbon sequestration. Optimal EMP combination has shown PMCS to be 169.81tonnes/yr for a cost of INR 2.034crores (USD 0.346 million). It was possible to reduce the cost further by INR 0.3crores (USD 0.051 million) taking recourse to lexicographic method, where the proposed OPTEMP-CSMO model minimizes cost keeping carbon sequestration same as PMCS. Many industries are responsible for producing greenhouse gases and therefore they can logically compensate for their GHG production by earning carbon credit. Depending on the need of carbon credit and financial constraint, one may decide to reduce the targeted carbon sequestration to reduce EMP cost. Thus, if a hilly residential area can be developed to have the maximum carbon sequestration through application of vegetative EMPs then a polluting industry can be asked to contribute fully or partially towards the implementation and maintenance of such EMPs area to earn carbon credit as a compensation for their GHG emission. Considering this, the OPTEMP-CSMO model is developed for the selection of EMPs in such a way that it restricts sediment and water yield from the watershed within permissible limits and also maximizes its carbon sequestration capacity at minimum possible cost.

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