Spatially Targeting the Expansion of Agricultural Land in a Mountainous Catchment for Maximal Sediment Export Avoidance: Heuristic Optimization Considering Spatial Interaction

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Abstract. Vegetation cover has a large impact on the soil loss dynamics of non-sealed, natural surfaces. Forests have meaningful effects on avoiding the production and transport of sediment. In this study, a combination of methods was applied to locate areas within a river catchment in the southern Andes of Ecuador that would produce a maximal or minimal impact on the sediment yield when deforested. RUSLE was applied to compute the amount of local sediment production within the study region. Then CAMF-MFD was used to simulate sediment flow throughout the catchment and to select cells with maximal/minimal impact on sediment yield at the catchment outlet and/or the urban border of the populated area within the catchment. Six scenarios were devised taking all possible combinations of two factors: reference areas (outlet, urban border, or the combination of both), and type of optimization (maximal- or minimal-impact afforested areas that would be converted to agriculture). The outcomes showed the results of CAMF-MFD are in the same order of magnitude as the sediment values obtained by related studies. Additionally, this work provides a means, based on scientifically sound methods, to discriminate between afforested areas that may be converted, in case it is required, to agriculture with a minimum impact on sediment

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yield, and afforested areas that must not, under any circumstances, be converted to land use types that are less protective to the soil.

Keywords: sediment production · flow and yield · deforestation · heuristic optimization · spatial interaction · CAMF · RUSLE

1 Introduction

Comprehensive land use planning requires the capability to integrate and analyze geospatial data from various sources and to tradeoff between different planning criteria complying with constraints. A specific planning task for which geospatial decision support systems are indispensable is the determination of the optimal sites in a landscape to perform a certain intervention [19,24,36].

Sediment delivery to rivers reduces channel and reservoir capacity and leads to water quality degradation and biodiversity decline because of suspended mineral and organic substances [9]. These issues are particularly undesirable in regions where the river is used as a source of drinking or irrigation water or for electricity production. Moreover, extreme discharge of water and/or sediment in populated places can cause catastrophic floods and mudflows. Forests have proven to be effective to reduce local runoff, sediment production and their downstream discharge and to alleviate the associated water quality decline [6,15,18,31]. Forests protect the soil surface against the ability of raindrops and runoff to detach and transport soil particles [20,33]. Agriculture, on the other hand, favors the detachment of soil particles through erosion and makes the detached materials more susceptible to being transported, especially in sloping landscapes. Therefore, expanding agricultural land use after deforestation will most certainly lead to an increase in local sediment production, transport and delivery to the downstream sedimentation sites and water bodies.

An important planning question for any afforestation or deforestation project is to identify the most suitable sites to plant or remove the trees, i.e. sites on which the objectives are achieved while complying with the constraints with maximal effectiveness. The discrimination between suitable and unsuitable sites for afforestation or deforestation typically depends on criteria adopted by forest managers, which range from maximizing societal and financial profits and minimizing on-site and off-site environmental consequences. In this study we address the selection of initially forested sites within a hydrological catchment with the objective to expand agricultural land while keeping the increase in sediment delivery to the river system and/or to urbanized zones to the minimum. In this way we intended to co-address the abatement of urban mudflows resulting from uncontrolled deforestation and agricultural expansion in peri-urban areas, especially within hilly or mountainous catchments.

As an alternative for exact optimization, [27,29,30] proposed the Cellular Automata for Minimizing Flow (CAMF) heuristic to locate the cells within a rasterized river catchment that should be forested to minimize the amount of sediment that reaches the outlet while accounting for the transport of sediment

between the cells. In this paper, we make use of the multiple flow direction variant of CAMF (CAMF-MFD, [3]). Whereas [3] applied CAMF-MFD in the context of afforestation, we deal for the first time with deforestation which is a pressing issue in Latin America and elsewhere across the globe.

2 Materials and Methods

2.1 The Cellular Automata for Minimizing Flow (CAMF) Heuristic

The original version of CAMF was introduced by [27] and further elaborated and evaluated in a number of case studies by [11,28–30]. CAMF finds the maximum- or minimum-impact cells in a raster dataset through iterative simulation of the local sediment production and flow considering spatial interaction (SI), followed by ranking the cells according to their impact, hence combining simulation and optimization. SI refers to the fact that changes in the state of a location can have an impact on the state of neighboring or even distant locations [13,14,34] so that the effect of an intervention at a particular location cannot be determined independently of the interventions in other locations [13,34]. In the case of CAMF, SI refers to the phenomenon that a land use change in a cell leads to changes of the local sediment production and local sediment transport capacity, which in turn affect the amount of sediment flowing from that cell into its downstream neighbor cells and, eventually, the sediment yield of the whole catchment. Accordingly, due to SI, changing the original land use type of a cell into agriculture will, in most cases, increase the sediment production and sediment transport capacity of that individual cell and, therefore, the sediment that flows into its neighbors and the river system. The original version of CAMF made use of a Single Flow Direction model. CAMF was later elaborated to include a Multiple Flow Direction (MFD) model in [3,10]. Moreover, [4] implemented and evaluated several elaborations of CAMF-MFD to reduce its computational requirements. Figure 1 shows the interaction of the modules for simulation and optimization incorporated in CAMF.

In this study, CAMF-MFD is applied as described and implemented by [3] for modeling sediment flow. In contrast to what was done by [3], where CAMF-MFD was applied to locate a predefined number of cells within a river catchment that should be changed from agriculture or pasture to forest in order to maximize the reduction of the amount of sediment that reaches the catchment outlet, we apply CAMF-MFD to determine the predefined number of cells that must or must not be changed into agriculture so that the increase in sediment delivery is minimized. Besides taking the outlet of the catchment as the reference cell for which sediment yield is to be minimized, we also consider the amount of sediment that is delivered to the cells that are part of the border of the major urban area in the study region.

In Fig. 1, in the preceding paragraph, and throughout the rest of this paper, the term ‘local sediment production’ refers to the amount of detached soil particles in each cell in each time step (year), while the term ‘sediment accumulation’ is used to designate locally-produced sediment plus sediment that leaves other

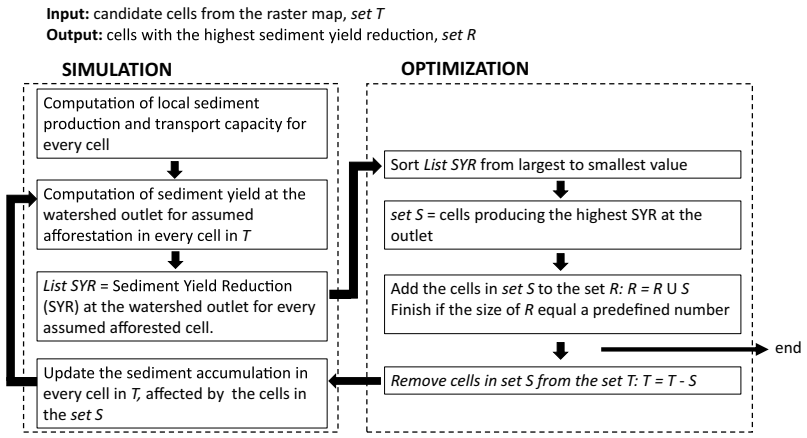


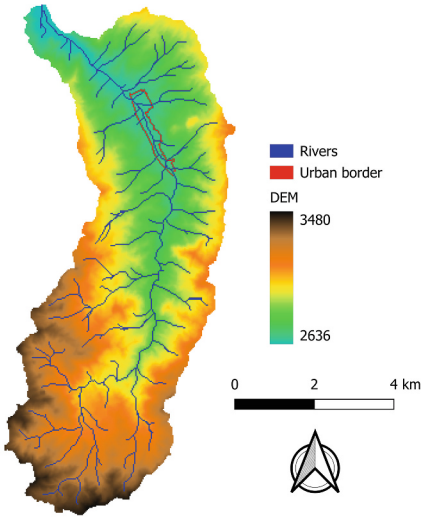
Fig. 1. Modules of CAMF to identify an optimal set of cells in a raster dataset while accounting for spatial interaction.

cells and that is delivered to the current cell. The term 'sediment yield' refers to the amount of sediment accumulation in the outlet cell(s) or in the cells that are part of the urban border. Hence, the only difference between sediment yield and sediment accumulation is that the former refers specifically to sediment accumulated in the outlet or urban border, while the latter refers to sediment accumulated in any cell of the catchment. The concept of 'sediment yield' is equal to what other authors call 'sediment export' or 'sediment loss'. In some cases, the term 'initial' is added as a prefix to indicate that sediment values correspond to the catchment under its initial land use distribution. This is in contrast with a 'final' situation, in which the selected cells are assumed to be converted to agriculture.

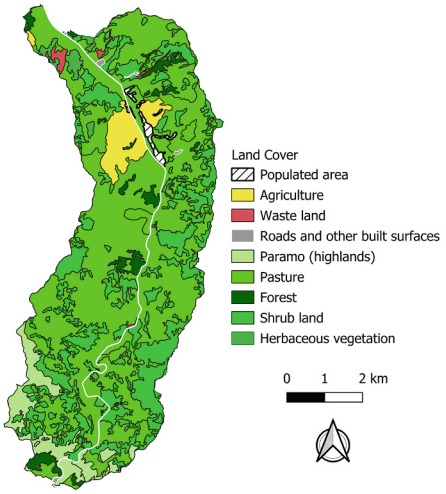
2.2 Study Region

The study region was the hydrological catchment of the Cumbe river, located in the province of Azuay, in the southern Andes of Ecuador, South America. The area of the catchment is around 45 km^2 and its altitude ranges from 2600 to 3500 masl. The Cumbe river is a tributary of the Paute river draining a basin, which has an area of 6442 km^2. The Paute river is important for hydropower generation, given that it is used as the source for the main hydroelectric production plants of the country, that generate around 38% of the hydroelectricity in Ecuador.

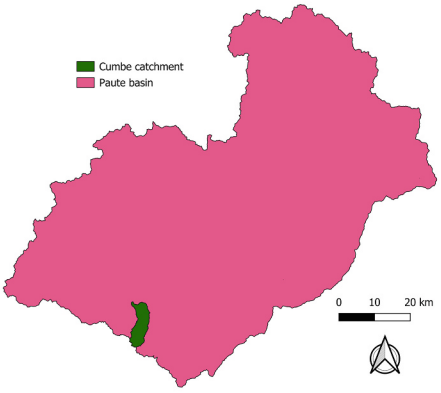
For the purpose of this study, the Cumbe catchment was represented by means of raster datasets with a resolution of 30×30 m. Figure 2a shows the Digital Elevation Model (DEM) and the river network of the Cumbe catchment while Fig. 2b shows the land use map compiled using data for 2009–2015 and published by the SIGTierras project of the Ecuadorian government (www.sigtierras.gob.ec). Figure 2c shows the location of the Cumbe catchment in the Paute basin and Fig. 2d the location of the Paute basin in Ecuador. The economy of Cumbe



(a) Digital Elevation Model (altitude values in masl), river network and the border of the urban center inf the Cumbe catchment



(b) Initial land use distribution in the Cumbe catchment (Source: SIGTierras project of the Ecuadorian government, www.sigtierras.gob.ec)



(c) Location of the Cumbe catchment in the Paute river basin



(d) Location of the Paute basin in Ecuador

Fig. 2. The Cumbe geodataset shown in this figure was downloaded from the SIGTierras project of the Ecuadorian government (www.sigtierras.gob.ec), and the geodatasets for the Paute basin and Ecuador were downloaded from the IDE system of Universidad del Azuay (Ecuador) (gis.uazuay.edu.ec).

depends mainly on agriculture and local commerce and is characterized by small markets and businesses.

2.3 Computation of Local Sediment Production

A fundamental input dataset required by CAMF is the local sediment production raster. To compute the local sediment production, the Revised Universal Soil Loss Equation (RUSLE), as proposed by [21], was applied. The RUSLE is shown in Eq. 1.

$$A = R \times K \times LS \times C \times P \tag{1}$$

where:

- R: Rainfall Erosivity factor [MJ mm ha^{-1} h^{-1} yr^{-1}]
- K: Soil Erodibility factor [T ha h MJ^{-1} ha^{-1} mm^{-1}]
- LS: Slope Length and Slope Steepness factor [unitless]
- C: Land Cover and Land Use factor [unitless]
- P: Support Practice factor [unitless]

The resulting soil loss value A (amount of detached soil particles) is expressed in T ha^{-1} yr^{-1}.

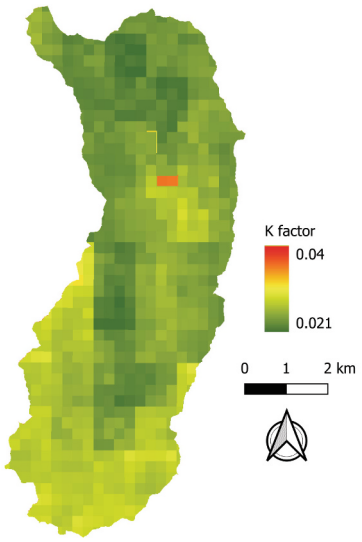
Rainfall Erosivity (R Factor). To compute the R factor, Eq. 2 [16,35] was chosen because only monthly precipitation data were available, rather than daily precipitation over a specific period of time as required by other models.

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5 \log_{10}\left(\frac{P_i^2}{P}\right) - 0.08188\right)} \tag{2}$$

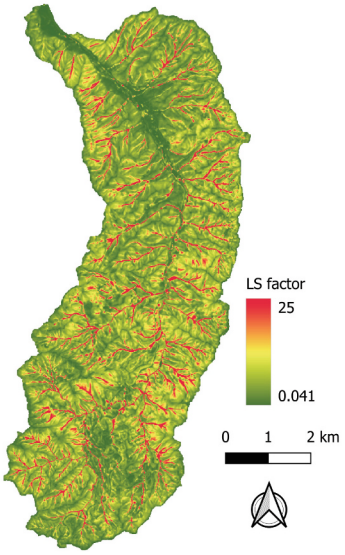
where:

- R: Rainfall Erosivity factor [MJ mm ha^{-1} h^{-1} yr^{-1}]
- P_i: Precipitation in ith month of considered year [mm]
- P: Annual precipitation [mm]

The monthly precipitation data originate from a hydro-meteorological station located at [LON -79 03' 00", LAT -3 03' 00"] in the Cumbe catchment. Using this dataset as a basis, the R-factor was computed for each year between 1964 and 2016. Following this procedure, an average annual R-value of 413 [MJ mm ha^{-1} h^{-1} yr^{-1}] was found. As a reference, the peak R value of approximately 824 [MJ mm ha^{-1} h^{-1} yr^{-1}] corresponds to 1993, and the lowest value of 124 [MJ mm ha^{-1} h^{-1} yr^{-1}] was occurred in 1980. The calculated R factor for the Cumbe meteorological station is significantly lower when compared to many other rainfall stations in the Andes (cf., for example, [5]), which is due to relatively low monthly precipitation values.



(a) K factor (resolution 250x250m) computed using Eq. 3 and the SoilGrids 2.0 database



(b) LS factor (resolution 30x30m) computed using Eq. 6 and the Digital Elevation Model

Fig. 3. K and LS factors for the Cumbe catchment.

Soil Erodibility (K Factor). To compute the K factor for the RUSLE, Williams' equation (Eq. 3) was applied. Details of this formulation can be found in [22].

$$K = 0.1317 \times f_{csand} \times f_{cl-si} \times f_{orgc} \times f_{hisand} \tag{3}$$

where:

- K: Soild erodibility factor [T ha h MJ^{-1} ha^{-1} mm^{-1}]
- f_{csand}: Sand and silt content in the topsoil [%]
- f_{cl-si}: Silt and clay content in the topsoil [%]
- f_{orgc}: Organic carbon content in the topsoil [%]
- f_{hisand}: Sand content in the topsoil [%]

The required data to apply Williams' equation were retrieved from the Soil Grids database version 2.0 (http://soilgrids.org). This database with global coverage offers soil characteristics at a 250×250 m resolution as derived from a machine learning approach. The considered depth of the topsoil was between 0 and 5 cm. The result is one K factor value for every cell, as shown in Fig. 3a.

Slope Length and Steepness (LS Factor). The Digital Elevation Model (DEM, 30×30 m) was the main input to compute the LS factor. The slope

length factor (L) was computed by means of the Desmet and Govers equation (Eq. 4).

$$L_{(i,j)} = \frac{\left[A_{(i,j)} + D^2\right]^{m+1} - A_{(i,j)}^{m+1}}{x^m D^{m+2} (22.13)^m} \tag{4}$$

where:

- $L_{(i,j)}$: Slope length factor in cell (i, j)
- $A_{(i,j)}$: Flow accumulation in cell (i, j)
- D: Pixel size
- x: Size coefficient (x = 1)
- m: Slope length exponent

The slope steepness factor (S) was computed using the piecewise function in Eq. 5.

$$S_{(i,j)} = \begin{cases} 10.8 \sin\theta + 0.03 & \text{if slope} < 9\% \\ 16.8 \sin\theta - 0.5 & \text{if slope} \geq 9\% \end{cases} \tag{5}$$

The final unitless LS factor was then computed by Eq. 6.

$$LS_{(i,j)} = L_{(i,j)} \times S_{(i,j)} \tag{6}$$

The resulting LS raster is shown in Fig. 3b. Its resolution is 30×30 m.

Cover Management (C Factor). Table 1 presents the values that were assigned to the C factor corresponding to each of the land use types found in the Cumbe catchment (see Fig. 2b).

Table 1. C factor value assigned to each land use type in the Cumbe catchment before (Initial C factor) and after (Final C factor) converting it to agriculture [10].

Land use type	Initial C factor	Final C factor
Populated area	0	0
Agriculture	0.2	0.2
Waste land	0.01	0.01
Páramo	0.0005	0.2
Pasture	0.003	0.003
Forest	0.001	0.2
Shrub land	0.003	0.2
Herbaceous vegetation	0.003	0.2

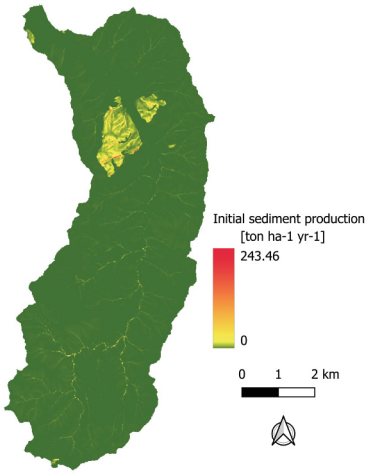
The lower C factor values in Table 1 express the presence of a protective artificial ('urban') or semi-natural cover ('vegetation') that reduces the production and transport of sediment (e.g., páramo, and forest). High C factor values correspond to land use types on which larger amounts of detached soil particles are available to be transported (e.g., agriculture). The column "Initial C factor" indicates the C factor values corresponding to the original land cover of the Cumbe catchment. The column "Final C factor" indicates the C factor values after deforestation/remove of vegetation (change into agriculture), for the land use types that can be deforested, that is, páramo, forest, shrub land and herbaceous vegetation. Cells in urban zones, waste land and grassland are not considered as candidates for removal of vegetation/deforestation; hence the final C factor value is the same as the initial value.

Conservation Support Practice (P Factor). The P factor represents the impact of local practices implemented to mitigate soil erosion. These practices can include terraces, contour farming, vegetative strips, or any other soil management techniques designed to reduce erosion. Such practices are not found in the Cumbe catchment. Therefore, in our application of the RUSLE equation, the P factor was set to 1. This value indicates that soil erosion is computed without any modification or benefit from conservation measures.

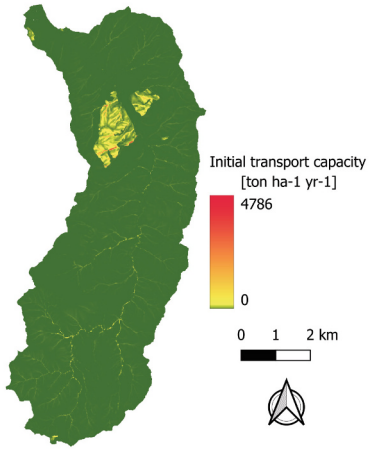
Average Annual Local Sediment Production (A). Once all RUSLE-factor datasets were computed, their resolution was uniformized by means of an upsampling procedure based on interpolation. Specifically, the datasets obtained from the Soil Grids database, whose original resolution was 250×250 m were upsampled to 30×30 m in order to make their resolution coincide with the other datasets. Next the RUSLE equation was applied to obtain the initial local sediment production for each cell in the rasterized representation of the Cumbe catchment (Fig. 4a). As expected, the agricultural zones and flanks of the river valleys stand out as the major sediment producing areas.

2.4 Computation of Transport Capacity (TC)

After computing the amount of detached soil particles available in each cell (Fig. 4a), the fraction of those particles that would effectively leave the cell as well as the fraction retained were computed. To this end, it was required to model the amount of sediment that flowing water can transport under specific hydrodynamic conditions, i.e. the sediment load. The Transport Capacity (TC) is defined as the maximum sediment load that can be transported from one cell to another in a given time step, i.e. one year. The TC acts as a threshold: the fraction of the total amount of local sediment in a cell that is below the TC will be transported and delivered to its neighbors, while the local sediment amount exceeding the TC value will be retained. The equation employing three of the factors used in the RUSLE (i.e., the R-, K- and LS-factors) proposed by [25,26]



(a) Initial local sediment production computed using RUSLE



(b) Transport capacity dataset computed using Eq. 7

Fig. 4. Local sediment production and transport capacity before deforestation for the Cumbe catchment.

was applied to compute the transport capacity in conditions with limited data available (Eq. 7).

$$TC = kTC \times K \times R \times T \tag{7}$$

where:

- TC: Transport Capacity [T ha^{-1} yr^{-1}]
- kTC: Transport capacity coefficient [m]
- R: Erosivity factor [MJ mm ha^{-1} h^{-1} yr^{-1}]
- K: Erodibility factor [T h MJ^{-1} mm^{-1}]
- T: Topographic factor [unitless]

The topographic factor was calculated using Eq. 8 [3].

$$T = LS - 4.12S_g^{0.8} \tag{8}$$

where LS is the slope length and steepness factor (unitless) and S_g is the normalized slope (unitless).

The kTC coefficient is a piecewise function of the C factor value (Eq. 9). To this purpose, a threshold value, kTC_{limit}, needs to be defined.

$$kTC_i^k = \begin{cases} kTC_{Low}, & \text{if } \zeta_i^k \leq kTC_{limit} \\ kTC_{High}, & \text{if } \zeta_i^k > kTC_{limit} \end{cases} \tag{9}$$

where ζ_i^k is the C factor for cell i before (k = 1) and after (k = 2) changing its land use type.

Based on the reasoning described in [2], the value for kTC_{limit} was set to 0.01 in line with [8], while the value for kTC_{Low} was set to 0.04 and kTC_{High} was set to 4, following [32].

The TC value for each cell was computed by means of Eq. 7, 8 and 9 at a resolution of 30×30 m. The resulting TC dataset is shown in Fig. 4b.

2.5 Scenarios

The CAMF-MFD-heuristic was applied to select the cells in the Cumbe catchment for which the replacement of the natural vegetative cover by agricultural fields would lead to minimal and maximal increase of the sediment yield at the outlet of the catchment as well as through the cells representing the perimeter of an urbanized settlement. Sediment export is a process subject to spatial interaction since it is the result of local production and displacement of soil particles along topographical flow paths governed by each cell's transport capacity.

The term 'candidate cells' stands for a subset of the cells representing the Cumbe catchment of which the land use type can potentially be changed to agriculture. In this study, cells under forest, pàramo, shrublands and herbaceous vegetation were considered as the candidates.

All input datasets of the CAMF-MFD heuristic are rasterized representations of the Cumbe catchment. Datasets are in a resolution of 30×30 m, and each raster comprises 429 (width) × 194 (height) cells. These settings result in a total of 83226 cells of which 16412 (19.7%) are considered as candidates for agricultural expansion. The problem to be solved is a combinatorial optimization problem whereby the cells to be selected are an optimal subset taken from the candidate cells.

Six different scenarios were studied:

1. Select a subset of candidate cells (total number of candidate cells: 16412), that is, 5% (821 cells), 10% (1641 cells), 15% (2462 cells) and 20% (3282 cells), that would produce a **maximum** increase in sediment reaching the **outlet** when converted to agriculture.
2. Select a subset of candidate cells, that is, 5%, 10%, 15% and 20%, cells that would produce a **minimum** increase in sediment reaching the **outlet** when converted to agriculture.
3. Select a subset of candidate cells, that is, 5%, 10%, 15% and 20%, that would produce a **maximum** increase in sediment reaching the **urban boundary** when converted to agriculture.
4. Select a subset of candidate cells, that is, 5%, 10%, 15% and 20%, cells that would produce a **minimum** increase in sediment reaching the **urban boundary** when converted to agriculture.
5. Select a subset of candidate cells, that is, 5%, 10%, 15% and 20%, cells that would produce a **maximum** increase in the total sediment reaching both the outlet and the **urban boundary** when converted to agriculture.

6. Select a subset of candidate cells, that is, 5%, 10%, 15% and 20%, cells that would produce a **minimum** increase in the total sediment reaching both the outlet and the **urban boundary** when converted to agriculture.

3 Results

3.1 Sediment Yield Before Deforestation

In the first stage, CAMF-MFD was executed to determine the amount of sediment delivered to the outlet of the catchment and/or the urban border under the original land use distribution (before deforestation). The computed sediment yield at the outlet was 2678.2 T yr^{-1}, at the urban border was 2596.31 T yr^{-1}, and the amount of sediment yield at both the outlet and the urban border combined was 2790.75 T yr^{-1}. The combined value of sediment yield shows that part of the sediment that is delivered to the urban border leaves those cells and eventually end up at the outlet cells. This is the reason why the combined sediment yield is not equal to the sum of sediment yield at the outlet and at the urban border. We can, therefore, infer that most of the sediment that reaches the outlet passes through the urban border. This behavior was expected, considering that the urban area in the Cumbe catchment is located in the valley along a segment of the river that is relatively close to the outlet. Additionally, the urban area is surrounded by agricultural parcels, which are among the main producers of sediment (see Fig. 2b and 4a).

[17] reports values of sediment yield for watersheds around the world that are between 0.01 and 64 T ha^{-1} yr^{-1}. [17] reports sediment yield levels of 6.74 and 5.97 T ha^{-1} yr^{-1} for the Tomebamba and Yanuncay watersheds respectively, which like the Cumbe watershed are located in the Paute river basin. It is evident that the diversity of sediment yield levels is a consequence of the characteristics of a watershed, e.g., land use, topography, rainfall depth, among others. The computed sediment yield values are in the order of magnitude of the data reported by [17]. The initial combined sediment yield in the Cumbe catchment (4500 Ha) reaches 2790.75 T yr^{-1}, that is, 0.62 T ha^{-1} yr^{-1}. This rather low sediment yield is explained by the fact that Cumbe is a well-preserved small watershed with most of its area covered by moorland, grassland, herbaceous vegetation, and shrub land. Another aspect that greatly influences these relatively low sediment yield values is the low rainfall erosivity (R factor) that was estimated for the Cumbe catchment using the precipitation dataset of the only meteorological station available in this region.

3.2 Scenarios 1, 3 and 5: Cells that Would Produce a Maximum Increase in Sediment When Converted to Agriculture

Table 2 shows the amount of sediment that would be delivered to the i) catchment outlet, ii) urban border, and iii) both the outlet and urban border combined when the land use type of 5, 10, 15, and 20% of the candidate cells is converted to agriculture (i.e., after deforestation). The values in the columns labeled as

'Sediment Increase' correspond to the number of extra tons per year with respect to the values obtained under the original land use distribution (Sect. 3.1). The values in the columns labeled as 'Sediment Yield' correspond to the sum of the amount of sediment under the original land use distribution in Sect. 3.1 plus the sediment increase values of Table 2.

Table 2. Results for Scenarios 1, 3 and 5 expressed in T yr^{-1}. For sediment increases, both absolute and relative (percentages between brackets with regard to values under initial land distribution) are reported

	Sediment Yield				Sediment Increase			
% selected	5%	10%	15%	20%	5%	10%	15%	20%
Outlet	5534.37	6582.82	7295.06	7769.51	2856.17 [107%]	3904.32 [146%]	4616.86 [172%]	5091.30 [190%]
Urb. border	5322.05	6294.51	6930.84	7318.67	2725.74 [105%]	3698.20 [142%]	4334.53 [167%]	4722.37 [182%]
Combined	5648.13	6696.60	7409.40	7884.48	2857.38 [102%]	3905.85 [140%]	4618.64 [165%]	5093.72 [183%]

Table 2 shows that there is an increase of more than 100% in the sediment yield in all scenarios. The sediment yield increase percentage decreasingly increases with increasing number of deforested candidate cells, and it approaches 200% when the percentage of deforested candidates is 20%. In all these scenarios, the closer a cell is to a riverbed, the more likely it is to be selected. Additionally, the C factor assigned to each land use type for the RUSLE equation (Table 1) has a fundamental effect regarding which cells are selected, for instance many maximum-impact cells correspond to páramo (land use type with minimum C factor and hence largest difference in C factor value compared to agriculture).

In Fig. 5 (results for Scenarios 1, 3 and 5), a lot of similarities can be observed between the outcomes for the river outlet and the urban border. This is mainly due to the intersection of the urban border and the river plus the fact that most of the cells around the urban border are already under agriculture.

Cells with maximum impact must not be converted to agriculture. Doing so would produce a large increase in the amount of sediment that is delivered to the river, with the corresponding negative consequences for drinking water provision, hydroelectricity production and biodiversity. Furthermore, converting these cells to agriculture would result in large amounts of sediment reaching the urban border, which considerably increases the risks of mudflows which is a recurring problem in Ecuador (e.g. [23]).

3.3 Scenarios 2, 4 and 6: Cells that Would Produce a Minimum Increase in Sediment When Converted to Agriculture

These scenarios were explored with CAMF-MFD in order to determine the areas (cells) that would produce a minimum impact on sediment yield increase at the outlet, the urban border, and in the combination of both if converted into agriculture. The results show that the selected cells would produce a negligible

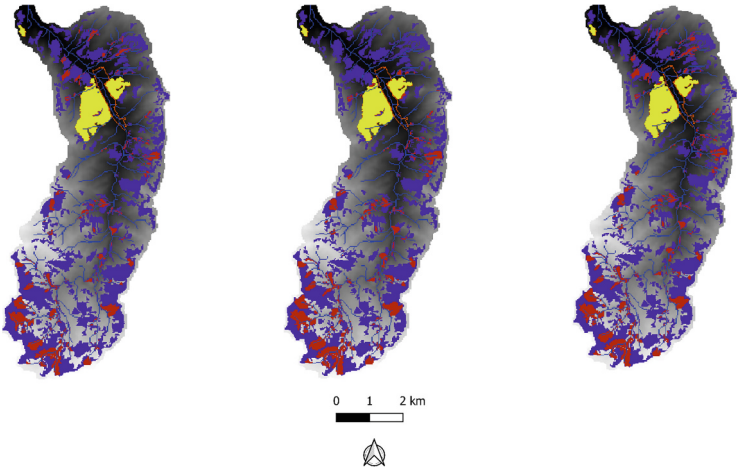


Fig. 5. Cells (20% of the candidates) with maximum impact (brown-red) regarding the increase in sediment delivered to the i) river outlet (left), ii) to the urban border (center), and ii) both outlet and urban border (right). Increasing elevation of each cell is indicated by a lighter gray shade. Purple cells indicate non-selected candidates. Yellow cells indicate the areas that were originally under agriculture. The river network is shown in blue, and the urban border is indicated in orange. (Color figure online)

increase in sediment delivery compared to the values in under the original land use distribution (Sect. 3.1). Therefore, in practice, at least 20% of the candidate cells can be converted from their original land use type to agriculture resulting in a negligible sediment delivery increase both at the outlet and at the urban border. These minimum-impact candidate cells may be converted to agriculture in case it is required.

Figure 6 (results for Scenarios 2, 4 and 6) shows that most cells with almost-zero-impact in sediment delivery to the catchment outlet (left) are located away from the river, which indicates the importance of the role of the river when considering the outlet as the target for our analysis. Specifically, the further away a cell is located from the river, the more likely is that the sediment leaving this cell will find "barriers" in its path to the river, where sediment will be retained. Additionally, most cells under páramo (see Fig. 2b) do not belong to the set of cells with minimum impact, which confirms that it is preferable to avoid human intervention on cells with large differences between the initial and the final C factor value, also when they are located far away from the rivers. This finding comes on top of the inherent value and importance of páramo for several other ecosystem services like water provision and biodiversity conservation as mentioned in [1,12]. In Fig. 6 (center) (cells with minimum impact to the urban border), most selected cells are located down-slope from the urban area, which is in agreement with intuition: changes in the land use type of such cells will not have any impact on cells up-slope, including the urban boundary. The map

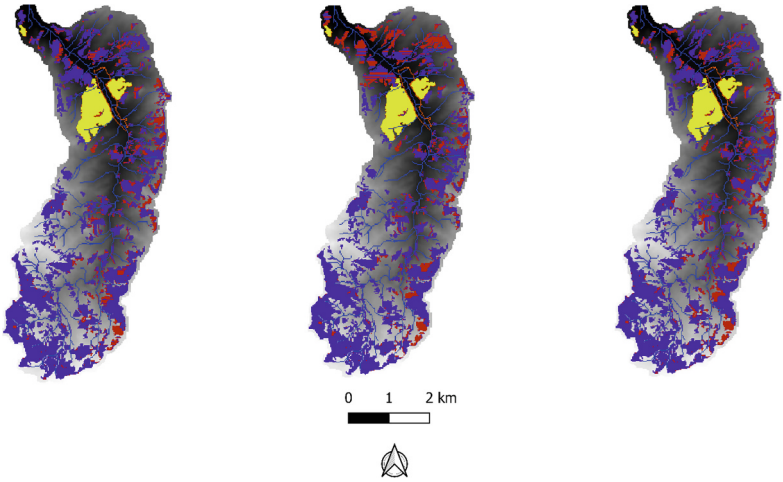


Fig. 6. Cells (20% of the candidates) with minimum impact (brown-red) regarding the increase in sediment delivered to the i) river outlet (left), ii) to the urban border (center), and iii) both outlet plus urban border (right). Increasing elevation is indicated by a lighter gray shade. Purple cells indicate non-selected candidates. Yellow cells indicate the areas that were originally under agriculture. The river network is shown in blue, and the urban border is indicated in orange. (Color figure online)

in Fig. 6 (right) (combined effects on both outlet and urban border) is quite similar to the map in Fig. 6 (left) (only outlet), which indicates that most cells with impact on the sediment delivery at the outlet clearly also impact the urban border.

4 Discussion and Conclusions

To increase the accuracy on the computation of the amount of sediment delivered, CAMF-MFD should include information about the contribution from unpaved roads and footpaths and from any other important sediment sources and channels (cf. [7]). Regarding the simulation process, the input data used to compute the R factor for the RUSLE were based on annual average rainfall in one station while a year-to-year and spatial variability of this factor would be more realistic. In case of afforestation the effects produced by this land use change will evolve through time. This holds but to a lesser extent also for deforestation, due to regrowth of vegetation after removal of the trees. This behavior is not currently implemented in CAMF-MFD.

In this study, the increase or decrease of sediment yield was the only criterion considered for the selection of optimal cells. Clearly, other environmental and socio-economic aspects would be of interest for simulation and optimization, such as maximization of water retention in forests and minimization of water

reaching riverbeds for land use planning. Likewise, CAMF can also consider a limited monetary budget for afforestation as a constraint.

This paper showed that CAMF-MFD is not only applicable to 'Where to afforest?' planning problems but also to questions like 'Where to deforest?' or 'Where to expand agriculture?' with minimization of sediment export from the catchment and/or minimization of sediment influx in urbanized areas as the objective function. The power of the iterative simulation followed by ranking approach implemented in CAMF-MFD is reflected in the speed of execution, the ranking of the selected cells aiding in priority setting and the possibility to extend it with region growing, financial and ecological budget constraints, and additional criteria beyond sediment delivery, both off-site and on-site.

The located cells that would produce a maximum sediment increase when its land use is converted to agriculture show that when the distance from a cell to the riverbed is short, the probability of that cell being selected is high. Therefore, changing the land use of those cells to agriculture would result in big amounts of sediment reaching the river outlet or the urban border, which considerably increases the risk of mudflows. Additionally, in these scenarios, land cover plays a fundamental role in the cells being selected. This is inferred from the fact that many maximum impact cells correspond to moorland (páramo).

In scenarios where minimum impact cells are to be selected, many of these cells produce no increase whatsoever in sediment yield when deforested. These cells should be considered first when an expansion of the agricultural land is deemed necessary. Additionally, the further away a cell is located from the riverbed, the more likely the sediment leaving this cell is to find "barriers" in the cell-to-river path.

Given that CAMF-MFD is a heuristic to identify sets of optimal cells in the presence of spatial interaction, it requires the integration of simulation processes for local sediment production and transport. The results show that both the optimization and simulation capabilities of CAMF-MFD and its computational performance are sufficiently promising to warrant further testing and elaboration to achieve a robust capability to identify regions in which an intervention (e.g., afforestation/deforestation) is to be applied without neglecting the spatially interactive nature of the impacts of the intervention.

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