Trading off Accuracy and Computational Efficiency of an Afforestation Site Location Method for Minimizing Sediment Yield in a River Catchment

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***Abstract*—The Cellular Automata based method for Minimizing Flow (CAMF) aims at selecting, from a rasterized database representing a river catchment, a predefined number of cells that should be afforested in order to minimize the sediment yield of the catchment. To this end, CAMF iteratively ranks cells according to sediment yield reduction, taking into account spatial interaction among cells. It was found during tests that the execution time of CAMF is directly proportional to the database size and the number of cells to be selected. This behavior can become a limiting factor for the applicability of CAMF to high resolution databases that cover large geographical areas. This issue motivated the necessity of exploring simplified CAMF variants that reduce its execution time and preserve the accuracy of its results. For this purpose, a simplified variant called on-site CAMF was devised, implemented and tested. On-site CAMF ranks cells based only on local cell information, i.e., the local sediment reduction that afforestation would produce in a cell, and the cell slope. During tests, on-site CAMF produced virtually the same results as the original version of CAMF in only a small fraction of the execution time. This means that, for these particular tests, spatial interaction did not influence CAMF output, possibly due to the number of cells that were selected, which was small with respect to the full geodatabase size. It is expected that spatial interaction becomes a relevant factor when larger sets of cells are selected.**

Keywords–Site location; Spatial interaction; Sediment yield; Optimization; Afforestation.

I. INTRODUCTION

Soil erosion is a common problem in tropical mountainous regions. In such regions, rainfall typically produces high levels of runoff, which in turn causes the soil to be eroded and, as a consequence, large amounts of sediment are produced, transported and deposited [1]. This often leads to the undesirable result of degraded soil, i.e., soil with severely limited performance in terms of fertility and productivity. A second negative consequence caused by soil erosion occurs when the sediment produced is delivered to the river system of a catchment. This sediment will be partially transported so that it will eventually reach the outlet of the catchment. This process is a critical factor when there exists a dammed reservoir downstream the river, since the sediment input to such infrastructures might produce high costs for sediment removal and a shortening of the reservoir lifespan given the resulting loss of capacity [2]. These factors make the study of sediment flow in mountainous regions crucially important.

One measure that has proven useful to control sediment production is afforestation ([3], [4], [5]), especially when it is technically planned and based on sufficient scientifically sound information. Typically, when planning an afforestation project, several criteria are to be considered simultaneously. Some of these criteria may pertain to the local performance of areas within the study region. This type of criteria are referred to as on-site. An example of on-site criteria is the amount of carbon sequestered both in soil and in biomass. On the other hand, some criteria can be related to the effect that changes in the state of a given area produce in the state of neighboring or even distant areas within the study region. These criteria are classified as off-site. Sediment delivery to the river and sediment yield of a river catchment are examples of this type of criteria. Both on-site as well as off-site criteria allow forest planners to discriminate between suitable and unsuitable alternatives, e.g., selecting sites for afforestation, choosing the species to be planted, or deciding when to harvest the forest.

The term site location for afforestation used throughout this paper refers to determining the exact locations in which trees should be planted. In this specific case, decision alternatives correspond to candidate sites within a river catchment that are available to be afforested. Only areas under agriculture and pasture are considered as candidates for afforestation. A single off-site factor, the amount of sediment at the outlet of the catchment, or sediment yield, was chosen as the decision criterion. Since the study regions are represented by raster datasets, the problem amounts to selecting a subset of cells (pixels) that should be afforested in order to minimize the

 ISBN: 978-1-61208-326-1

sediment yield of a river catchment.

A computational iterative method to tackle this problem was proposed in [6]. This method aimed to select, at each iteration, the cell(s) that, in case of being afforested, would produce the maximum reduction in sediment yield. The name Cellular Automata-based method for Minimizing Flow (CAMF) was used to refer to this method. To select a cell or cells at each iteration, CAMF computes the sediment yield reduction that would be produced considering that every candidate cell is afforested separately. This sediment yield reduction values is then used to build a ranking from which the optimal cell(s) is (are) selected.

Some limitations were identified in CAMF. One of these limitations is the fact that scoring cells and building the ranking are relatively expensive procedures in terms of execution time. A second limitation is that there is a high probability that only one cell is selected at each iteration, so that many iterations of CAMF are necessary in order to select the required number of cells. This undesirable combination of repeating many times a computationally expensive procedure might restrict the applicability of CAMF when dealing with high resolution datasets that cover extensive study areas.

This work aimed at providing insights about several aspects of CAMF. First, the performance of CAMF was examined as a function of the size of the database to which it is applied and of the number of cells to be selected. This analysis produced indicators about the applicability of CAMF to large databases, which are frequently found in natural resources management projects. This goal was meant to complement the work reported in [6], where only very small, sample databases were used during tests. The second general aim was to propose a variant of CAMF that addresses its limitations to drastically reduce its execution time while preserving the quality of the results it produces.

Section II introduces the study regions and the corresponding geodatabases that were used during tests. This section also explains CAMF and its on-site variant in detail as well as the performance indicators that were collected during tests. Section III presents and discusses the results produced by CAMF and its on-site variant. Finally, Section IV draws some conclusions and proposes a few points that require further work.

II. Materials and Methods

A. Study regions

Three raster geodatabases were used for testing CAMF. These geodatabases, stored using the ArcInfo ASCII grid format, represent nested river catchments located in the southern Andes of Ecuador using a cell resolution of 30x30 m. The study regions and their corresponding geodatabases are introduced below.

1) The Paute river catchment: The Paute river catchment is located in the southern Andes of Ecuador. Its area is 5055 km^2. Altitudes in this catchment vary between 1591 and 4651 m asl. High sediment production rates have been measured in this catchment in the past [1] and several dammed reservoirs that are part of one of the most important Ecuadorian hydroelectric complexes are located within this catchment. The location in Ecuador and the sediment production of the Paute catchment are shown in Figure 1. The areas under agriculture and pasture in this catchment correspond to a total of 1483 km^2 (around 30% of the full area of the catchment).

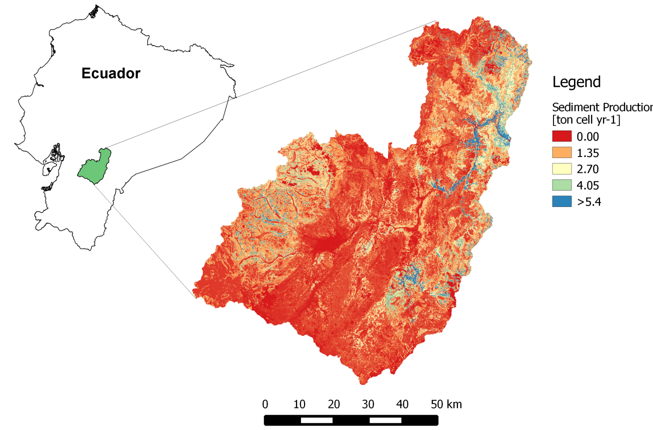

Figure 1. Location and sediment production of the Paute catchment. Cell size is 30x30 m

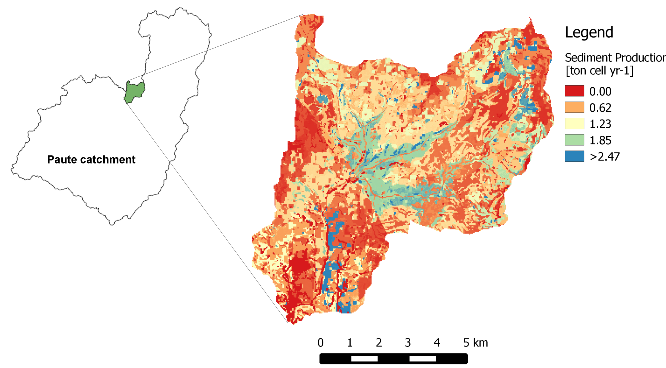

Figure 2. Location and sediment production of the Tabacay catchment. Cell size is 30x30 m

2) The Tabacay river catchment: Tabacay is a subcatchment of the Paute catchment. Its total area amounts to 66.3 km^2. The altitudes are in the range between 2481 and 3732 m asl. The importance of studying sediment production and transport in this catchment is given by the fact that the Tabacay river, besides being a tributary of the Paute river, is used as the source for provision of drinking water to the city of Azogues. Agriculture and pasture cover a region of 24 km^2 in the Tabacay catchment (39% of the total catchment area). Figure 2 depicts the location of Tabacay within the Paute catchment and its sediment production.

3) The Tabacay500 database: The third database used in tests corresponds to a part of the Tabacay catchment, which represents an area of 1.7 km^2 around its outlet. The codename Tabacay500 was chosen for this database because it comprises 500 cells (26% of the full area) that are considered as the initial candidates for afforestation. The location of the region represented by this database within Tabacay and its sediment production are displayed in Figure 3.

 ISBN: 978-1-61208-326-1

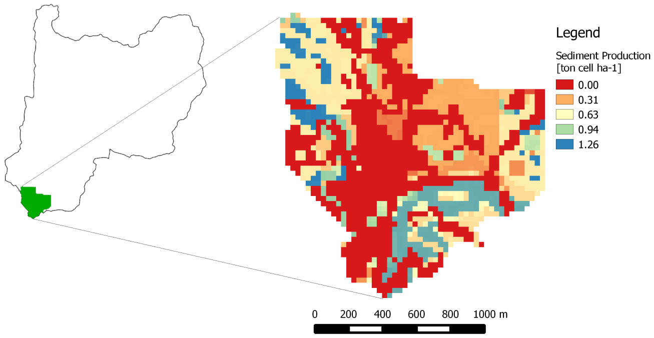

Figure 3. Location and sediment production of the region represented by the Tabacay500 database. Cell size is 30x30 m

B. Cellular Automata based method for Minimizing Flow (CAMF)

[6] introduced a computational iterative method aimed to locate sites that, after afforestation, would result in the minimization of the sediment yield of a river catchment. In [6], the acronym CAMF is used to refer to this method, which is described in the following subsections.

1) Required input data: To execute CAMF the following input data are required:

Sediment production:
: This is a raster dataset containing values about the sediment produced locally in each cell, expressed in $ton\,cell\,yr^{-1}$;

Retention capacity:
: If the amount of sediment in a cell is smaller than its retention capacity, expressed in $ton\,cell\,yr^{-1}$, it is assumed that no sediment leaves that cell;

Saturation threshold:
: The amount of sediment in a cell that exceeds the saturation point, expressed in $ton\,cell\,yr^{-1}$, is assumed to be fully delivered to its steepest downslope neighbor;

Flow factor:
: Raster dataset that indicates the fraction of the amount of sediment in a cell that is delivered to one of its neighbors. This fraction is applied only when the amount of sediment in a cell is in the range between the retention capacity and the saturation threshold;

Flow direction:
: CAMF uses a Single Flow Direction (SFD) dataset based on the Deterministic 8 (D8, [7]) method to determine the flow path that sediment follows within a catchment. The D8 method assumes that flow leaving a cell is delivered only to its steepest downslope neighbor;

Solution size:
: Parameter set by the user of CAMF to indicate how many cells should be selected to be afforested.

Two different versions of each of the first four datasets listed above are required: 1) a dataset representing the initial situation, that is, the catchment under its original land cover; and 2) a dataset that represents the catchment in case every cell was under forest. These two versions of each of the four datasets are used by CAMF to compute the amount of sediment that leaves each cell. The flow direction dataset is used to simulate the transport of the sediment within the catchment. In other words, the flow direction dataset allows to incorporate spatial interaction into CAMF, which in turn permits the involvement of off site criteria, like sediment yield.

2) Workflow: CAMF is an iterative method that comprises the following steps:

1) The sediment accumulation in each cell is computed. Sediment accumulation refers to the sediment locally produced in a cell plus the amount of sediment that it receives from its neighbors;
2) For each candidate cell, the sediment yield reduction that would occur in case that cell is afforested is computed;
3) A ranking of all candidate cells is built based on the sediment yield reduction values computed in the previous step;
4) The cell or cells at the top of the ranking that correspond to the maximum score are selected as part of the solution;
5) The sediment accumulation values are updated for the selected cells and for all the cells that are between each selected cell and the outlet;
6) If the total number of selected cells is less than the solution size, repeat from step 2.

As a first step, an implementation of CAMF as described in [6] and outlined above was produced. This implementation is referred to as ‘original CAMF’. The purpose of implementing and testing original CAMF was threefold. First, to explore the applicability of CAMF to databases that are larger than the ones used in [6]. The second objective was to produce reference values for comparison to the variant of CAMF introduced below. The third objective was to approximate the average number of cells that are selected by CAMF at each iteration.

After studying original CAMF, two issues were pinpointed that can compromise the computational efficiency or even the applicability of this method, namely:

1) At each iteration, CAMF computes the sediment yield reduction that would be produced in case every single candidate cell in the catchment was afforested. Depending on the extent covered and on the resolution of the database, the number of candidate cells can reach several millions. Note that the computation of the sediment yield reduction for a single cell requires simulating the sediment transport from that cell to the outlet. After this has been done for every candidate cell, a sorted list of cells (ranking) is built. It was expected then that the computational time required to build this ranking is relatively high.
2) Once the ranking is built, only the cell or cells at the top of the ranking that correspond exactly to the maximum sediment yield reduction are selected. It is unlikely that many cells correspond exactly to the same sediment yield reduction value. As a consequence, it was expected that only one cell is

 ISBN: 978-1-61208-326-1

selected at each iteration, which would result in a limited use of the computationally expensive ranking mentioned above.

As mentioned above, sediment yield minimization is an example of an off-site criteria. This means that the sediment yield reduction that is produced when a given cell is afforested not only depends on local information, but also on information pertaining to other cells, i.e., the outlet and all cells in the steepest descent path between it and the considered cell. As already explained, computing sediment yield reduction values in CAMF involves the notion of spatial interaction, which is intuitively appropriate, especially for the case of sediment transport in mountainous regions. On the other hand, taking spatial interaction into account is a decision that contributes to a large extent of the computational cost of original CAMF in terms of execution time. This issue is dealt with by the CAMF variant proposed in the following section.

C. On-site CAMF

On-site CAMF aims at avoiding the extra computational cost that considering spatial interaction introduces into CAMF operation. In on-site CAMF, the notion of spatial interaction is simply disregarded and only local (on-site) information is used to rank cells. The motivation of on-site CAMF is based on the claim made by [6], which states that, in general, cells with steep slopes and high local sediment production are selected by CAMF. Based on this conclusion and considering that these two factors correspond to on-site information that was readily available for the study regions, they were chosen as the basis to compute scores that allow to produce a cell ranking in this variant of CAMF. The score assigned by on-site CAMF to a cell was computed using (1).

$$s_i = w_f f_i + w_e e_i \qquad (1)$$

where

- s_i is the score assigned to cell i.
- w_f and w_e are user defined parameters that can take values in the range [0, 1] and indicate the relative importance (weight) assigned to each factor, either slope or sediment production, respectively, with $w_f + w_e = 1$.
- f_i is the normalized (scaled to the range [0, 1]) slope of cell i.
- e_i is the normalized change that would be produced in local sediment production when cell i was afforested, that is the difference in sediment production between the initial situation and the afforested situation.

Note that cells with higher values for s_i will be preferred to be selected. Note as well that both slope and local sediment production values do not change during the execution of this method, which means that on-site CAMF is not an iterative method and, therefore, all required cells are selected in a single step.

D. Methodology

1) Performance measures: The experimental phase consisted in several executions of both original and on-site CAMF for the three databases described in Section II-A for solution sizes corresponding to 1, 10, 100 and 1000 cells. During each test, several performance factors were recorded, namely:

Sediment yield reduction:
: Decrease in the sediment yield of a catchment (with respect to the initial situation) when the required number of cells are afforested;

Execution time:
: CPU time necessary to produce the required output;

Number of iterations:
: Number of iterations performed by original CAMF to produce the required output;

Spatial coincidence:
: This is a comparative performance measure applicable only to on-site CAMF. It uses the output (cells selected for afforestation) produced by original CAMF as a reference. Spatial coincidence was computed as $\frac{n_c}{n}$, where n_c is the number of common cells selected by both original and on-site CAMF, and n is the solution size. Therefore, a spatial coincidence of 1 indicates that both methods selected exactly the same set of cells.

2) Parameter values: The different input datasets and parameter values used when executing all versions of CAMF are listed in TABLE I. The values corresponding to retention capacity and saturation threshold were arbitrarily set in such a way that around half of the available sediment under the original land cover leaves the river catchment in a time unit (year).

III. Results and Discussion

A. Original CAMF

The output and performance measures obtained after executing original CAMF are shown in TABLE II. The sediment yield reduction in case the corresponding number of cells are afforested is shown as an absolute value in the second column and as a percentage with respect to the initial sediment yield in the third column. The last column shows the average number of cells that are selected at each iteration.

It is clear from TABLE II that sediment yield reduction values for Tabacay500 and Paute increase almost proportionally with respect to the solution size, which is an indication that at least 100 cells in Tabacay500 and 1000 cells in Paute perform almost equally well when afforested. This is not the case for Tabacay, where such proportionality is evident only when comparing the sediment yield reduction corresponding to solutions sizes of 1 and 10. This proportionality is not present when solutions sizes of 100 and 1000 cells are considered. Except for Tabacay500, execution times seem to increase also in a direct proportion with respect to solution sizes. This is given by the fact that in almost all cases the number of iterations performed by original CAMF is equal to or slightly smaller than the corresponding solution size. This effect is less noticeable for Tabacay500, for which only very short times are

TABLE I. INPUT DATA AND PARAMETER VALUES USED DURING EXPERIMENTATION PHASE

Input/Parameter		Dataset/Value
Sediment production $[ton\,cell\,yr^{-1}]$		Available datasets (Figure 1, 2 and 3)
Retention capacity $[ton\,cell\,yr^{-1}]$	initial	Paute: 0.27, Tabacay: 0.17, Tabacay500: 0.075
	afforested	Paute: 0.54, Tabacay: 0.34, Tabacay500: 0.15
Saturation threshold $[ton\,cell\,yr^{-1}]$	initial	Paute: 0.81, Tabacay: 0.51, Tabacay500: 0.225
	afforested	Paute: 1.08, Tabacay: 0.68, Tabacay500: 0.3
Flow factor [-]	initial	Slope linearly scaled to [0, 1]
	afforested	Initial flow factor divided by 2
Flow direction [-]		Computed from DEM, based on D8 [7]
Solution size		1, 10, 100, 1000

TABLE II. PERFORMANCE MEASURES CORRESPONDING TO ORIGINAL CAMF

Solution size	SYR $[ton\,yr^{-1}]$	% SYR	CPU time [s]	# iterations	Cells/iteration
Tabacay500 (initial SY: 370 $ton\,yr^{-1}$, total cells 1892, candidate cells 500)					
1	0.498	0.1	0.015	1	1.00
10	4.971	1.3	0.046	10	1.00
100	46.665	12.6	0.109	97	1.03
Tabacay (initial SY: 29075 $ton\,yr^{-1}$, total cells 68123, candidate cells 26850)					
1	3.308	0.01	0.234	1	1.00
10	32.171	0.11	1.872	10	1.00
100	199.806	0.69	17.799	99	1.01
1000	924.975	3.18	155.002	927	1.08
Paute (initial SY: 3212203 $ton\,yr^{-1}$, total cells 5616679, candidate cells 1647304)					
1	14.729	0.0005	133.646	1	1.00
10	147.205	0.0046	1311.625	10	1.00
100	1470.557	0.0458	11556.164	87	1.15
1000	14675.398	0.4569	93484.394	701	1.43

required. In this case, internal details of the implementation and even technical aspects related to the way in which the algorithm is executed by the operating system take a higher relative importance with respect to factors pertaining to the method itself, like simulating sediment flow and building the ranking of cells.

Unexpectedly, in all tests involving solution sizes of 100 and 1000, the number of cells selected per iteration by original CAMF is greater than one. This finding indicates that the probability of more than one cell corresponding to exactly the same maximum sediment yield reduction at a given iteration plays a role in practice. This may be an indication that the function applied to compute the amount of sediment leaving a cell and the way in which sediment flow is simulated, play a homogenizing role for the computation of sediment yield reduction values. On the other hand, in all those tests, the average number of cells selected per iteration is still close to one. This characteristic may make CAMF execution times unnecessarily long.

Database size, in terms of number of candidate cells, has a clear impact on execution times. This is explained by the fact that larger database sizes will require more cells to be processed at each iteration. When comparing the execution times obtained for Paute to the corresponding values for Tabacay, a clear proportionality is found. This is not the case when execution times for Tabacay and Tabacay500 are contrasted. This may be the result of (very short) execution times for Tabacay500 being largely influenced by internal, technical aspects of algorithm execution. When considering execution times separately, it can be argued that they start to play a restrictive role for large databases like Paute. Specifically, original CAMF requires more than 3 hours to select 100 cells in Paute, and almost 26 hours for a solution size of 1000 cells. Additionally, it is important to note that the solutions sizes tested are rather limited, considering the full size of the database, especially for the case of Paute.

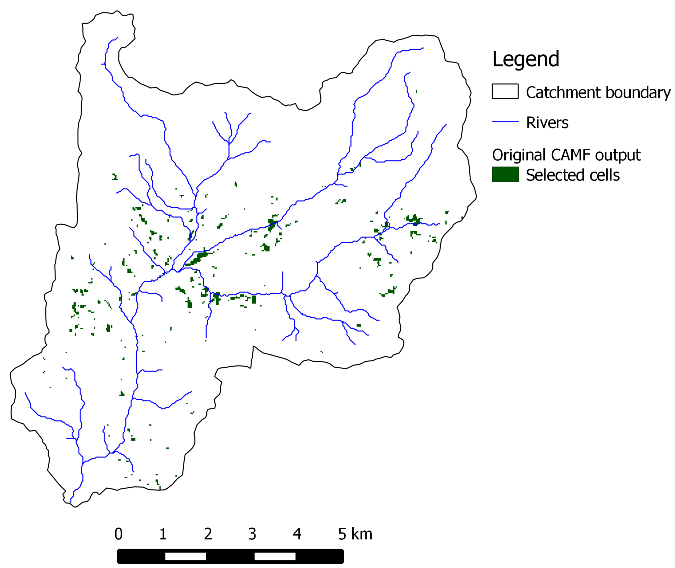

Figure 4. Output of original CAMF for a solution size of 1000 cells in Tabacay

Figure 4 shows the 1000 cells that were selected by original CAMF in Tabacay.

B. On-site CAMF

The first step conducted when applying on-site CAMF was to determine sensible values for the relative importance parameters corresponding to slope and sediment (w_f and w_e in (1)). In this case, a naive trial-and-error approach was used, based on testing different combinations of values for w_f and w_e to score, rank and select cells and assessing the corresponding values of sediment yield reduction produced when the selected cells were afforested. The tested parameter values and the resulting sediment yield reduction values are listed in TABLE III.

The values in columns 2 to 6 of TABLE III show the ratio between the sediment yield reduction produced by on-site CAMF when the relative importance parameters were set to the values indicated in the headers and the sediment yield reduction value produced by original CAMF for the corresponding database and solution size. From this we can conclude that setting $w_f = 0.01$ and $w_e = 0.99$ produces the best results from among the tested combinations. This means that slope plays a very limited role in cell selection in CAMF, whereas local sediment reduction appears as the most relevant factor in this regard. These values were used in all tests performed with on-site CAMF to produce the performance indicators listed in TABLE IV. Column 'SYR fraction' shows the ratio between the absolute sediment yield reduction resulting from on-site CAMF and original CAMF. Similarly, 'CPU time fraction' lists the ratio between the execution time of on-site CAMF with respect to original CAMF.

It can be seen from TABLE IV that on-site CAMF produces practically the same results as original CAMF. A first interpretation of these results is that spatial interaction does not play a role for the combination of databases and parameter values used during the tests. Considering the values set for the relative importance parameters (w_f and w_e), it can be argued that the local sediment reduction information, that is, the amount in which sediment production would decrease in every cell when afforested, is virtually the only factor that is determining which cells are selected.

Stating that spatial interaction does not play a role when sediment transport simulation in particular, and off-site criteria in general, are involved may seem counter intuitive. However, this finding can be supported by the fact that relatively limited solution sizes were used during the tests, especially for the cases of Tabacay and Paute. When a limited number of cells are to be selected from a large number of candidate cells, it can occur that most selected cells in fact does not interact with each other, which means that they do not share a meaningful segment of their path to the outlet and therefore, changes in the state of one cell do not affect the state of other selected cells. It can be claimed that the river may act as an element that produces interaction among cells, since sediment leaving most cells will eventually reach and be transported by the river to the outlet. However, the river plays the role of a transport channel, that is, it does not really influence the sediment yield attributed to a given cell, or the sediment yield reduction produced when that cell is afforested. This means that all sediment that leaves a cell and reaches the river will be fully transported to the outlet of the catchment, at least for the parameter values used during the tests, especially regarding retention capacity and saturation threshold. It is expected that using larger solution sizes would lead to an increased probability of spatial interaction occurrence among selected cells. In that case, it can be foreseen that on-site CAMF would produce significantly different results with respect to original CAMF, also this claim is not backed up by the output of on-site CAMF for Tabacay500.

Regarding execution times of on-site CAMF, it is clear that they are not influenced by solution size, since once the ranking is built it takes about the same time to select any number of cells from it. On the other hand, execution times are indeed influenced by the database size, since the time spent building the ranking of cells will depend on the number of candidate cells. CPU time fractions show the dramatic reduction on execution time that is observed when spatial interaction is left out of consideration and when all cells are selected in a single step, instead of using iterative selection.

IV. Conclusions

[6] proposed a technique called CAMF with the aim of selecting from a rasterized database representing a river catchment a set of cells to be afforested in order to minimize the sediment yield of the whole catchment. In this paper an implementation of CAMF was produced and its performance was tested on three databases representing nested river catchments in the southern Andes of Ecuador, with the aim of analyzing the behavior of CAMF when applied to databases that differ greatly in size. In addition, the influence of the number of cells to be selected on the performance of CAMF was assessed.

In contradiction to what was initially expected, the number of cells selected at each iteration by original CAMF was not exactly 1 in all tests. This indicates that the possibility of two or more cells having exactly the same sediment yield reduction value at a given iteration, although limited, does exist. However, since the observed deviation from 1 is small or, in other cases, the number of selected cells per iteration is exactly 1, execution times increase almost in direct proportion with respect to solution sizes. Besides solution size, the number of cells comprised in the database has also a clear impact on execution times. This fact allows to conclude that execution time can become a limiting factor for original CAMF, specifically in cases in which it is applied to high resolution databases covering large extents and using large solution sizes. This restriction would be even more apparent in such contexts when several runs of original CAMF are necessary, as it could be the case when performing scenario analysis, or when using original CAMF as a component of an integral model or method that requires to execute it repeatedly in a systematic way.

A variant of CAMF called on-site CAMF was also proposed, implemented and tested on the same databases as the original CAMF. On-site CAMF uses only local cell information, i.e., sediment reduction and slope, to score and rank cells. Tests using on-site CAMF produced very similar results with respect to original CAMF outputs, in an almost negligible, constant execution time. One interpretation of this finding may be that for these specific combinations of databases, solution sizes, and parameter values, spatial interaction does not play a role. This observation can be attributed to the fact that solution sizes used in tests are limited when compared to the full database sizes. It is assumed then that, when larger solution sizes are used, the relevance of the spatial interaction role will significantly increase. It is expected that, in such cases, on-site CAMF would produce different results with respect to original CAMF.

 ISBN: 978-1-61208-326-1

TABLE III. OUTPUT OF TUNING PROCEDURE FOR RELATIVE IMPORTANCE VALUES FOR ON-SITE CAMF

Solution size	$w_f = 0.5$ $w_e = 0.5$	$w_f = 0.75$ $w_e = 0.25$	$w_f = 0.25$ $w_e = 0.75$	$w_f = 0.1$ $w_e = 0.9$	$w_f = 0.01$ $w_e = 0.99$
Tabacay500					
1	0.91	0.90	0.91	0.91	1.00
10	0.95	0.94	0.96	0.98	1.00
100	0.89	0.81	0.99	0.99	0.99
Tabacay					
1	1.00	1.00	1.00	1.00	1.00
10	0.80	0.57	1.00	1.00	1.00
100	0.60	0.42	0.88	0.99	0.99
1000	0.70	0.57	0.88	0.96	0.99
Paute					
1	1.00	1.00	1.00	1.00	1.00
10	1.00	0.99	1.00	1.00	1.00
100	0.99	0.98	1.00	1.00	1.00
1000	0.98	0.93	0.99	1.00	1.00

TABLE IV. PERFORMANCE MEASURES CORRESPONDING TO ON-SITE CAMF

Solution size	SYR [$ton\, yr^{-1}$]	SYR fraction	CPU time [s]	CPU time fraction	Spatial coincidence
Tabacay500 (initial SY: 370 $ton\, yr^{-1}$, total cells 1892, candidate cells 500)					
1	0.498	1.00	<0.001	0.000	1.00
10	4.971	1.00	<0.001	0.000	1.00
100	46.398	0.99	0.015	0.138	0.99
Tabacay (initial SY: 29075 $ton\, yr^{-1}$, total cells 68123, candidate cells 26850)					
1	3.308	1.00	0.062	0.265	1.00
10	32.171	1.00	0.062	0.033	1.00
100	197.504	0.99	0.046	0.003	0.98
1000	913.868	0.99	0.093	0.001	0.97
Paute (initial SY: 3212203 $ton\, yr^{-1}$, total cells 5616679, candidate cells 1647304)					
1	14.729	1.00	3.135	0.023	1.00
10	147.205	1.00	3.088	0.002	1.00
100	1470.557	1.00	3.634	0.000	0.98
1000	14675.398	1.00	5.834	0.000	0.97

It is clear that CAMF behavior depends heavily on the values set for its parameters. This is especially true for the retention capacities and saturation thresholds for every cell. Values for these and other parameters must be carefully determined, in order for CAMF to reproduce real world phenomena in a valid way. A systematic and scientific sound calibration procedure becomes a requirement in this regard. However, such a procedure most likely would involve a more detailed consideration of sediment production and transport, which lies beyond the scope of this paper.

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