Detection of hot spots of soil erosion and reservoir siltation in ungauged Mediterranean catchments

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Abstract

The long-term average, distributed parameter PhosFate model was applied for erosion hot spot identification in unmonitored Mediterranean catchments. Based on experiences of previous case studies in well-monitored watersheds, the model was tested in a study over the entire area of Albania with success. The model results were validated by the sporadically available data on river discharge and sediment loads. With an optimization method cost-effective interventions were planned to efficiently reduce soil erosion. The optimization algorithm is based on a simple sediment transport model and it minimizes the necessary area of interventions. In accordance with the critical source area concept, it was shown that intervention with better management practices on properly selected, a few percent of the total area is sufficient to reach a significant reduction in soil loss, reservoir siltation and consequently an improvement in water quality.

Keywords: Albanian river basins, cost-effective management, PhosFate model, sediment transport, soil erosion.

1. Introduction

Soil erosion is almost immeasurable at source; it is hard to identify the area of origin and complicated to manage due to their spatial and temporal variability, complex transport pathways and strong relations to hydrology and soil properties. Because of these characteristics, management of the agricultural soil loss

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and reservoir siltation problem essentially needs watershed level approximation and model simulations [1]. It is especially necessary, if the river monitoring system is underdeveloped or water quality data are not available. Evaluation of different management scenarios is usually based on model simulations as well. Strategic analyses and decisions related to national water quality management programs or management plans of larger river basins are usually based on larger scale models ([2], [3] and [4]). Local water quality investigations and practical measures rely on smaller scale modeling results.

Local erosion rates in themselves are quite rarely evaluated in respect of water quality. River sediment loads and concentrations (or sediment volume) arising from the local soil losses at the sub-catchment outlets or impoundments are usually used to evaluate the siltation status. However, the desired river load reductions caused by the planned interventions as the overall management results of the whole catchment have to be finally addressed to local fields within the watershed. Soil loss reduction with the same rate in the whole catchment or areas having erosion rates over a certain threshold value would be an equitable solution, but it surely would not provide a cost-effective management. Not all of the source areas effectively contribute to the river loads and the extent of their contribution depends on the transport efficiency of the eroded materials within the catchment and towards the outlet. Management efforts should be concentrated on the critical source areas where transfer of pollutants from land to water probably occurs [1]. Therefore, only a transport-based management approach can be environmentally and economically effective.

We present a simple modeling approach, which calculates soil erosion and suspended sediment (SS) transport within a catchment. The model is able to find the most significant source areas contributing to the river loads and provides an optimized, cost-effective management alternative to reduce soil erosion even in the absence of detailed environmental data.

2. Materials and methods

The catchment-scale phosphorus (P) emission model PhosFate [5] was applied to evaluate the SS fluxes of the pilot areas. PhosFate was developed for watershed management purposes. The model is appropriate to support decision-making in watershed management. It allows planning best management practices (BMPs) in catchments and simulating their possible impacts on immissions based on the critical source area concept. The model was validated in several types and sizes (from a few to ten thousands of km^2) of well-monitored catchments in Central Europe (Hungary, Austria and Switzerland [5], [6], [7] and [8]). The good performance in both arid and wet regions on all spatial scales showed the model's ability to predict the hot spots of erosion and diffuse P pollution in unmonitored catchments. PhosFate is a semi-empirical, long-term average, distributed parameter model. The model computes the main elements of the hydrologic cycle, the soil erosion, local P emissions and SS and P transport in the terrestrial areas and throughout the stream network. The model is able to predict climate change impacts on emissions as well.

2.1. Annual erosion and sediment transport modeling

Soil loss is estimated using an adopted version of the Universal Soil Loss Equation (USLE, [9]). Parameters of USLE are related to meteorological data (rainfall intensities and heights within the simulation period) and various digital maps about catchment properties (topography, slope, physical soil type, topsoil humus content, landuse classes, land management practices). Area-specific annual soil loss values were calculated for every cell. The parameters of USLE were determined according to the literature [10] and [11] and were kept unchanged during the modeling. Exceptions are the simulation period dependent rainfall energy factor (as a proxy of the meteorological properties, which can represent

climate change impacts) and the erosion protection factor, which can vary according to the desired agricultural practice.

SS transport is computed by joining the individual cells according to the flow tree. Each cell is characterized as either field or channel cell based on a threshold value of upstream catchment area. The outflowing flux from each cell is the difference between the inflowing flux plus the soil loss and the net sediment retention via settling. Net sediment deposition is computed from the inflowing load value with an exponential function of the cell residence time.

Residence time depends on the average flow velocity, which is calculated for both overland and channel flow with the Manning-equation [12]. Average hydraulic radius is estimated with a power function of the upstream catchment area of the given cell [13]. Manning roughness parameters are related to the land use classes [12] and [13]. Deposition rate of the retention formula was calibrated. Different deposition parameter is used for the terrestrial and in-stream transport. Thus, sediment load can be calibrated with two adjustable parameters only, which should be adapted to local conditions. Reservoirs are considered for the channel transport as well, whereas reservoir residence time is calculated from the inflowing discharge and the operation volume. Discharge is calculated according to the long-term water balance model WetSpa [14]. Results of the calculations are the spatial distribution of the soil loss and the SS load values at any arbitrary point within the catchment, the SS retention pattern of the catchment and the cell residence time and travel time values to the outlet.

2.2. Hot spot identification and optimization

There are many BMP alternatives and their combinations, which can be effective in reducing emissions ([1] and [10]). The model particularly focuses on the rural land use management. It includes source-control and transport-control interventions. Source controls (land use conversions, nutrient management, cultivation method changes) are planned to reduce emissions at their source by reducing the soil contamination or the volume of the runoff and soil loss. Transport-controlling measures (buffer zones, swales and constructed wetlands) are implemented to retain SS and particulate P during their transport in the field and the riverbed. Their impact appears in reducing flow velocity. After modifying the agricultural management related model factors or the land use map and running the emission and the transport model according to the designed modifications the load reducing efficiencies can be simulated.

To identify the cells, which are possible candidates for interventions, a tolerable soil loss value was determined (10 tons per hectare and years in this study). Management scenario analysis was executed according to several individual intervention methods (forestation, grassland development, contour planting, and soil stabilization) in those agricultural areas, where the computed specific soil loss rate is higher than the tolerable value. In case of buffer zones, all watercourses with an upstream catchment area higher than 10 km^2 were protected by a forest zone along the channel.

To achieve an optimal management (highest reduction in emissions at the lowest cost), not all emission source areas have to be addressed by the interventions, because they contribute differently to the river loads. Tracking the transport pathways from each cell, the most promising locations for an intervention can be selected. The cells, which succeed to send the biggest amount of eroded material to the stream network, can be considered as ideal subjects to source control (reduction of local erosion). The latter layer indicates the main transmitters, which probably have limited rate of erosion, however, they transport significant amounts of SS coming from their immediate vicinity. These are the best places for transport control, *i. e.* to establish retentive zones (mostly along streams). Ranking the cells on both maps, a priority sequence can be derived for the interventions, which forms the basis for an optimized intervention calculation. The optimization can be governed by two objective functions (either load reduction efficiency at fixed available cost or cost efficiency at fixed pollution limit). The two

intervention types (source and transport control) must be harmonized during the calculations. If a highly erosive cell is treated by intervention, the relative importance of their downstream neighbors also reduces. Similarly, by the allocation of a buffer zone, the effective contribution of the upstream neighbors declines. Thus, the importance ranking of cells must be updated after each intervention act in a specific cell.

The algorithm of calculation is the following:
1. Estimate to achievable gain for each cell.
2. Intervene (change landuse) in the cell with the highest possible gain.
3. Actualize the model calculations in the affected region (up- and downstream neighbors of the intervention cell).
4. If the budget is spent, finish the procedure, else repeat from the beginning (1).

3. Case study region: Albania

Albania has a total area of 28 750 km^2, is located between the coasts of the Adriatic and Ionian seas and the Balkanian mountain chains. It has a dense river network with seven main rivers, which flow from E to W. Catchments of river Buna, Drini and Vjosa have considerable part lying in the neighboring countries, thus, the total hydrographical catchment area of the Albanian rivers is 43 300 km^2, *i. e.* one third of the total catchment is out of the country.

Soil loss via water erosion in Albania is a widespread phenomenon. Soil loss is 2-3 times higher in Albania than in other Mediterranean countries and 10 to 100 times greater than in many other European countries. The typical Mediterranean climate is one of the most aggressive ones in terms of erosion (heavy rainfall intensities, high rainfall amounts, drought as a permanent phenomenon, *etc.*). This together with the topographic and soil conditions (steep slopes, silty soils, low humus content) already classifies about more than 50 % of the total area in Albania as naturally erosive. This is amplified by the anthropogenic impacts (forest cutting, cultivated steep slopes, up-down cultivations, bare soils after harvesting, overgrazing, absence of erosion protection measures) resulting in significant soil loss rates. Consequently, coastal areas and terrestrial reservoirs are highly subjected to increased SS loads and thus, to accelerated siltation.

Local measurements on hydrology and erosion are extremely scarce and mostly historical. However, the international scientific literature contains several estimates on the erosion and sediment transport in the Mediterranean region. Nevertheless, the various authors report a wide range of soil loss and sediment transport level of the country. [15] states a national average soil erosion rate of 27.2 tons per hectare and year, which results in an annual sediment flux of 60 million tons carried by the Albanian watercourses. [16] presents an estimation of soil erosion for the whole country, they computed a soil loss rate more than 10 tons per hectare and year for a remarkable part (in the center and south) of the country and even more than 100 tons per hectare and year at three smaller regions also in the south. [17] reports a soil loss range of 20-100 tons per hectare and years for Albania and they computed for the north, middle and south-east region of the country an annual average agricultural erosion rate of 15, 53 and 37 tons per hectare and year, respectively.

[18] reports about 83 million tons per year suspended sediment fluxes transported by the main Albanian rivers into the Adriatic and Ionian seas. [19] published a lower average load entering the seas with a value of 52 million tons per year, however, the fluxes can vary in a wide range between 30 and 120 tons per hectare and years. From the literature data net SS loads were determined which consider the SS loads generated in the Albanian territory only (*e. g.* Drini and Vjosa rivers flow from abroad into the country, but the input data cover only the Albania part of their watershed). The main rivers were used for the model calibration. Their discharge can significantly vary according to the current climatic conditions.

River flow can reduce by 40-50 % in dry years and increase by 40-70 % in wet years. Variation of SS flux is wider, it is from -40 % up to 140 % according to the climate.

4. Results and discussion

The erosion module of the PhosFate model was applied for the whole territory of Albania considering long-term average conditions. To perform a countrywide assessment on erosion and sediment transport a GIS database was compiled according to the model demands. The necessary digital maps (*e. g.* topography, soil characteristics, humus content, land cover and vegetation) and climate data (rainfall, meteorology) were collected from different international data sources. Besides these, river monitoring data on discharge and SS loads as well as results of other erosion studies were also collected from the literature to calibrate the model and execute comparisons. Data for the modeling were collected from international databases and publications on the erosion and its related and important fields.

4.1. Model calibration

Modeled versus „measured" (determined from the literature data) long-term average net (generated in Albania) river flow and SS load values are presented in Fig. 1a and Fig. 1b, respectively. Parameters of the hydrological module of PhosFate, the USLE equation and the transport algorithm were adjusted manually in order to achieve a reasonable fit with the measured ones. Special key factor of the erosion in Albania is the overgrazing of the pastures and woodlands. Pastures, sparsely vegetated areas and the semi-agricultural lands were considered as potential candidates for overgrazing. Their plant coverage parameter was set close to the values of croplands and bare soils (the same was assumed for orchards to take into account grazing effect between the plantations or trees).

Discharge simulations fit quite well the observed data, there are small relative inaccuracies (about 30 % overestimation) in case of Ishmi, Erzeni and Semani In case of SS load, the picture is a bit more problematic. The order of magnitude of the observed loads are well predicted by the model, however, some remarkable deviations can be recognized. In Mati and Ishmi there is a quite significant model error by 60 % over- and 50 % underestimation, respectively. Erzeni, Drini and Vjosa have also some local differences (30-40 %) compared to the estimated values.
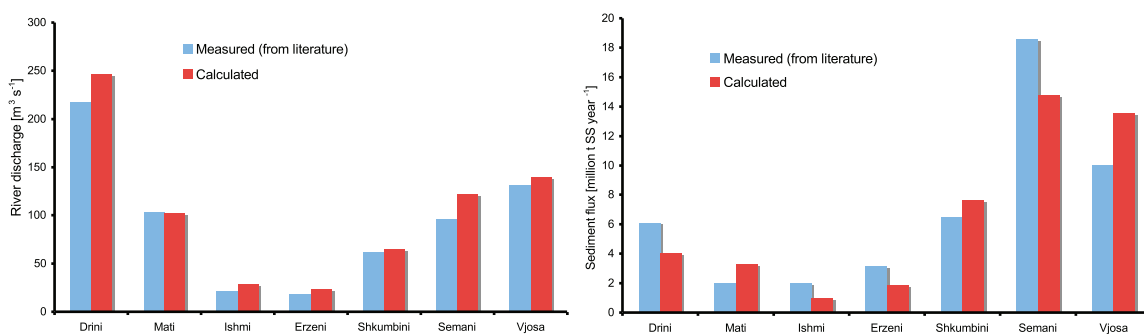

Fig. 1. (a) Simulated and reported long-term average net river flow of the Albanian rivers; (b) Simulated and reported long-term average net SS flux of the Albanian rivers.

Uncertainties in the modeling procedure have three clear sources. The first main source is the input data set. Several maps have low resolution, as they were acquired from global datasets so the small-scale

heterogeneities can't be considered. Besides this, statistics data are usually missing or scarcely available in questionable quality. The second source of uncertainty is the model itself with its assumptions, mathematical approximations and simplifications. The backbone USLE equation is highly empirical, therefore its parameters may differ in a new region. Precise setting of USLE-factors should be based on local conditions. The third component of uncertainties is the reference data set, which was considered as "reality" when the model was calibrated. Due to the overwhelming weight of large-scale estimates in the dataset, the uncertainties in the reference data regarding local soil loss and sediment transport are surely immense. Occasional river sediment fluxes measurements and sediment trap data were the only possibilities to check the performance of any soil erosion calculations. The local measurement of soil loss is very difficult, it can cover only a small field, it requires special equipment plus it has remarkable costs, thus, it had not been applied in the study region.

Considering these uncertainties and the availability of the data, the computed results are satisfying. More detailed information could significantly improve the model performance at local scale and provide the possibility to refine the model parameters or apply more sophisticated approaches. However, despite the limitations and uncertainties of USLE, its improved or revised forms are widely used as long-term soil loss estimator and engineering tool for choosing BMPs to control erosion [20].

4.2. Soil erosion

The calculated soil loss rates of Albania are shown in Fig. 2a. There is remarkable soil loss in the whole territory, but it is especially significant in three main regions, which are located in the north, in the central part of the country and in the south. In these regions, similarly to [16], high soil loss rates can be found with values more than 10 tons per hectare and years, but values even more than 100 tons per hectare and years appear also quite frequently. Countrywide average soil loss rate is 31.5 tons per hectare and year, which is far above the tolerable limit of 10 tons per hectare and years, but it fits the average rate reported by [15]. The average rate means totally 90.5 million tons soil eroded annually in the country. Distribution of the higher soil loss classes is demonstrated in Table 1, 78 % of the territory produces tolerable erosion, and 22 % (6399 km^2) has higher soil loss rate than the tolerable limit. However, this 22 % of the total area is responsible for the majority (93 %) of the soil erosion.

Fig. 2b shows the potential soil loss source areas, which have higher erosion rate than a tolerable or critical value. Red color indicates the sources being under agricultural cultivation, while green areas represent the naturally covered regions, which can also produce significant erosion. 76 % of the source areas (4875 km^2) is agricultural land. The natural areas (1523 km^2) cause the background SS loads of the river system.

Moderate slopes up to 7 % do not generate high soil losses for both specific and total values. Over 7 % slope the soil loss values ate increasing and reaching a value more than 40 tons per hectare and year. Over 24 % the specific value is slightly rising only, however, due to the high share of the steep regions in the country, the total soil loss volume is much higher in the steepest class (about 57 million tons per year) than in the others. 63 % of the total soil loss comes from the steepest regions of the country, while below 12 % steepness the contribution to the total erosion is very low.

Extremely high soil loss rates (60-130 tons per hectare and years) were calculated for the mixed agricultural land and the orchards/vineyards located on high slopes. This results in an enormous total soil loss (82 million tons per year) from the total agricultural sector. The mixed lands (especially the semi-natural lands), the grasslands, the sparsely vegetated areas probably used as intensive pasture and they candidate for overgrazing, which leads to high erosion rate. Besides this, it is important to note, that the special monthly distribution of the rainfall in Albania highly strengthens the impacts of erosion, because most of the rainfall events occur in the winter half-year, when agricultural soils are often uncovered. The

naturally covered areas remain at low erosion rates at the country level. 92 % of the total soil loss comes from the agriculture (or areas affected by the agriculture, *e. g.* overgrazed natural lands), while 8 % can be considered as background erosion.
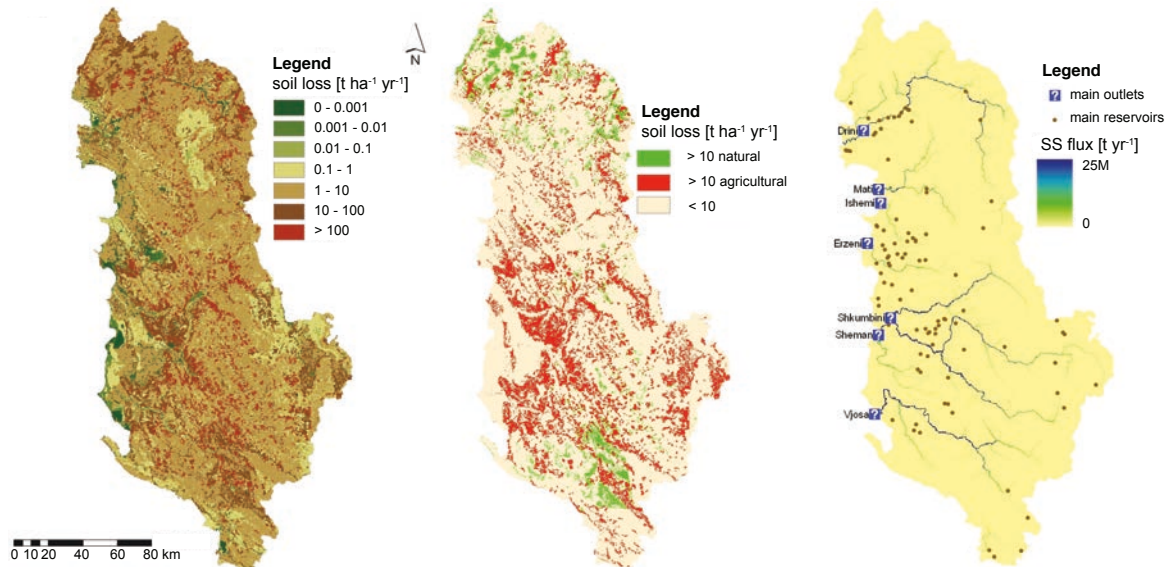

Fig. 2. (a) Calculated long-term average specific soil loss rates in Albania; (b) Agricultural and natural source areas of soil erosion in Albania; (c) Sediment transport by the main watercourses of Albania.

Table 1. Areas, total amounts and proportions of the specific soil loss rate classes in Albania.

Soil loss rate t ha^{-1} year^{-1}	Area km^2	Area proportion %	Total soil loss 10^6 t year^{-1}	Soil loss proportion %
<1	6556.3	22.8	0.2	0.3
1-10	15795.2	54.9	6.3	7.0
10-100	4121.6	14.3	12.6	13.9
>100	2277.0	7.9	71.4	78.9

4.3. Sediment transport

Despite the huge total soil loss (90.5 million tons per year) generated in the country, only *ca.* 55 million tons suspended sediment is transported by the rivers into the seas annually (Fig. 2c). Consequently, about 40 % of the eroded soil material cannot reach the seas because of the retention while sediment is transported from the source to the recipients. Considerable sediment retention via settling can occur either on the terrain when the surface runoff velocity reduces (decreasing slope, changing land cover) or in the river systems when the flow velocity drops due to hydraulic alterations of the channel (reservoirs, vegetated channels, sections with slow velocity and flow on the floodplain).

In total, 53 million tons per year SS flux is transported out of the country. The highest sediment loads are carried by the river Semani and Vjosa into the seas. About 18 % of the suspended solids fluxes discharged from the sub-catchments into the river systems are retained in the river channels, mainly in the reservoirs. The highest sediment retention occurs in river Drini, which has a huge reservoir at Fierze (its

surface area is about 70 km^2), where majority of the sediment load is retained. Without the reservoir the river would carry almost 20 million tons annually. Reservoirs have significant impacts in Mati and Ishmi rivers as well. Remarkably sediment retention can be recognized on the terrestrial field also, it is about 21 % of the total soil loss in average (slightly varying among the sub-catchments). At country level, 59 % of the eroded soil volume is transported to the seas, the sediment retention is equally distributed between the field and the reservoirs.

4.4. Management of the source areas and optimized interventions

Among the BMP alternatives forestation and proper grassland management are very efficient, almost 90 % of the original soil loss is remains on the field if forestation or grassing is applied. They have almost similar reduction efficiency, there is no considerable difference between their impacts, excepting if grassland is used as pasture. Poaching by animal hoofs and overgrazing can highly reduce the efficiency of the grassland. In case of forest, a certain time period is needed for developing a dense forest, so in the first couple of years the forests remain at lower efficiency until reaching their maturity. Buffer zones along the streams have only small impacts on soil loss at country level (7 %) because the interventions consider the riverside zones instead of the source areas. Agricultural soil protection without any soil stabilization is limitedly successful only (17 %), however, if it is accompanied by vegetative soil stabilization (*e. g.* mulching on the bare soil or grassing between the permanent crop rows/fruit trees), the efficiency approximates the value of the forests (74 %). Decrease of the sediment flux due to the interventions is similar to the soil loss reductions for the source control measures. However, buffer zones can provide remarkable SS retention (12 %) by filtering their fluxes when they pass the zone. Buffer zones are insufficient as individual intervention, however, they can enhance the source controls with an additional transport control, consequently the intervention areas at the source can be reduced. Management an agricultural area of 4875 km^2 (17 % of the country area) can produce impressive soil loss reduction, however it does not consider cost efficiency.

The optimization method was applied for the whole country. The objective was set to reach the highest load reduction with intervening on maximally 4.5 % of the total area. The load reduction was efficient (Fig. 3a). The achievements of intervention varied by watershed, from 50 % (Erzeni) to 68 % reduction (Vjosa). Similarly, the spatial distribution of intervention locations was not homogeneous in the country (Fig. 3b). There were 3 main zones where a significant proportion of interventions concentrated. These areas are the hotspots for erosion and sediment loads on the country level. In the lower Drin watershed the optimal intervention zones covered large, uninterrupted areas on the catchments of some tributaries. However, in the middle and Southern mountainous parts the erosion hotspots formed several independent smaller zones, which are harder to manage. This shows that the manageable erosion-sensitive areas are easier to delimit in some northern parts, while this property shows a much higher spatial variability in the rest of Albania.

Erosion has a very high spatial heterogeneity in the whole country, just like in other parts Europe. This highlights the fact that management should first identify the small-scale locations where best management practices can effectively reduce both erosion and the siltation of the surrounding stream network. Simultaneously, this high variability makes it possible to implement very effective (50-80 % reduction) prevention measures by the application of best management practices on a minor proportion (around 5 % instead of 17 %) of the total catchment areas. Certainly, as erosion is more intense on agricultural areas, the affected proportion of cropland and orchards is higher, typically 10-15 % of this category is affected by measures. But the variety of BMP methods allows continuing agricultural production in these zones with minor modifications that reduce erosion.
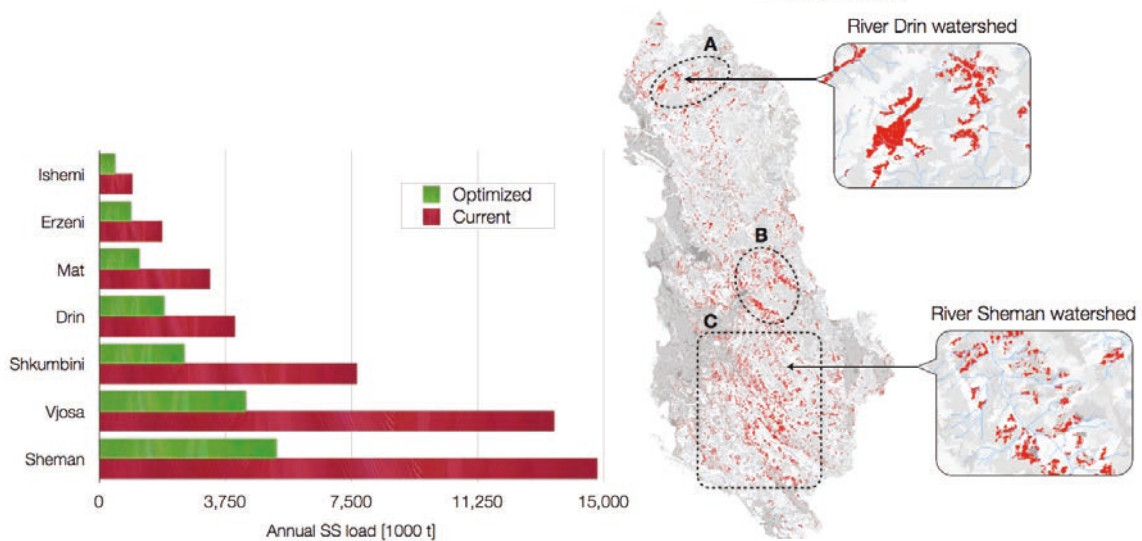
Fig. 3. (a) Optimization results (load reduction) for the entire Albanian territory, (b) Optimized intervention locations in Albania (on the right). A, B and C are the easily manageable erosion hotspot zones. The magnified parts show the different spatial arrangement of intervention zones in the Northern and Southern parts of the country).

5. Conclusions

Countrywide average soil loss is about 30 tons per hectare and year. 22 % of the country area has higher soil loss rate than the tolerable value (10 tons per hectare and year). This 22 % is responsible for the majority (93 %) of the soil erosion. Main source sector is the agriculture, which generates *ca.* 90 % of the total soil loss, especially agricultural lands located on high slopes. The main Albanian rivers transport considerable SS loads to the seas, *ca.* 60 % of the total soil loss amount can reach the coastal zones. According to both international experience and an adapted model application, the erosion potential is highly variable in Albania, too. Hotspots that contribute most to the soil loss and the siltation of streams are frequently separately positioned small areas.

Management scenarios can effectively reduce the local soil loss and the sediment fluxes as well. Both natural vegetative cover and agricultural cultivation with erosion control can be successful. If intervention measures are concentrated on the highly contributive areas, an immensely effective management can be achieved without having to transform the overall landuse practice on most of the catchments. Introducing BMPs on a carefully selected few percent of the total area can cut the total amount of erosion and also the transported material fluxes by half or even more.

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