MAPPING OF EROSION REGULATION ECOSYSTEM SERVICES

Boris Markov¹, Stoyan Nedkov²

¹ Sofia University, borismarkov@abv.bg;
² Assoc. Prof. NIGGG-BAS, Akad. G. Bonchev str. bl. 3. snedkov@abv.bg;

Abstract

Ecosystem services are the benefits that humans receive from the environment. Soils provide many ecosystem services required to support human well-being. Soil erosion is one of the major and most widespread forms of soil degradation. This study examines how erosion regulation can be evaluated and mapped. To map the erosion regulation, as an ecosystem service, we use indicators that incorporate four USLE factors – soil erodibility (K), cover-management (C) and slope length and steepness (LS). Erosion regulation map was generated by GIS-based overlay analysis of these factors. The capacity to provide erosion regulation service was assessed using relative scale that ranges from 0 (no relevant capacity) to 5 (very high relevant capacity). The results reveal the potential of the factors to supply ecosystem services. The assessment of ecosystem’s capacity to regulate soil erosion can provide important information for environmental management.

Keywords: Ecosystem services, Erosion regulation, GIS, USLE

1. INTRODUCTION

All economic activity and most of human well-being are based on a healthy, functioning environment. By focussing on the various benefits from nature – ecosystem services – we can see more clearly the direct and indirect ways that human well-being depends on the natural environment (TEEB, 2010). Ecosystems are shaped by the interaction of communities of living organisms with the abiotic environment. An ecosystem is usually defined as a complex of living organisms with their (abiotic) environment and their mutual relations (Maes et al., 2013). Ecosystems range from those relatively undisturbed, such as natural forests, to landscapes with mixed patterns of human use, to ecosystems intensively managed and modified by humans, such as agricultural land and urban areas. Ecosystem services are the benefits people obtain from ecosystems (MA, 2005). Other cited definitions are: “...the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life” (Daily, 1997); “…the benefits human populations derive, directly or indirectly, from ecosystem functions” (Costanza et al., 1997); “…components of nature, directly enjoyed, consumed, or used to yield human well-being” (Boyd and Banzhaf, 2007).

Ecosystems provide a variety of benefits to people, including provisioning, regulating, cultural and supporting services. Provisioning services are the products people obtain from ecosystems, such as food, fuel, fiber, fresh water, and genetic resources. Regulating services are the benefits people obtain from the regulation of ecosystem processes, including air quality maintenance, climate regulation, erosion control, regulation of human diseases, and water purification. Cultural services are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences. Supporting services are those that are necessary for the production of all other ecosystem services, such as primary production, production of oxygen, and soil formation (MA, 2003). Ecosystem goods (such as food) and services (such as waste assimilation) represent the benefits human populations derive, directly or indirectly, from ecosystem functions. For simplicity, ecosystem goods and services are referring together as ecosystem services. A large number of functions and services can be identified (Costanza et al., 1997). Ecosystem functions are the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly” (de Groot et al., 2002). Ecosystem services are, in turn, derived from ecosystem functions and represent the realized flow of services for which there is demand (Maes et al., 2013). Regulation functions relate to the capacity of natural and semi-natural ecosystems to regulate essential ecological processes and life support systems through bio-geochemical cycles and other biospheric processes. In addition to maintaining ecosystem (and biosphere) health, these regulation functions provide many services that have direct and indirect benefits to humans (such as clean air, water and soil, and biological control) (de Groot et al., 2002). Regulating ecosystem services are by nature closely related to ecosystem structures, processes and functions. Erosion regulation is the ability of the ecosystems to prevent and mitigate soil erosion (Burkhard, 2014).
Soil erosion is one of the most serious environmental problems in the world today, as it seriously threatens agriculture, natural resources and the environment. Soil erosion is a natural process, occurring over geological time, and most concerns about erosion are related to accelerated erosion, where the natural rate has been significantly increased by human activity. Accelerated soil erosion is a serious concern worldwide, and it is difficult to assess its economic and environmental impact accurately because of its extent, magnitude, rate and the complex processes associated with it (Erkal and Yuldirim, 2012).

In this study we investigated the capacity of the ecosystems to regulate soil erosion in a case study area of Strumeshnitsa river catchment in Bulgarian territory. The objectives of this study are:

- To analyze factors that affect soil erosion and their relation to ecosystem services supply
- To choose appropriate method for mapping erosion regulation ecosystem services
- Highlight the areas with high erosion regulation capacity

2. MATERIALS AND METHODS

2.1 Study Area

The catchment of Strumeshnica river is located in the southwest-most part of Bulgaria (Figure 1), (41°31” - 41°52” N, 22°91” - 23°29” E) with an area of 440 km². In terms of geomorphology, from north to south three major units are located: Ograzhden mountain, valley of Strumeshnitsa and Belasitsa mountain. The highest point in the region is peak Radomir (2029 m). The altitude varies between 78 m and 2029 m above sea level. The mean elevation is about 587 m. About 30 % of the territory is characterized by steep slopes more than 20°. The climate is classified as mediterranean with dry summer and wet winter.

Strumeshnitsa river originates from the Plachkovica mountain in the Republic of Macedonia and flows into the Struma river. It has a total length of 114 km, of which 81 km in the Republic of Macedonia and 33 km in Bulgaria. The soils in the study area are represented by three main soil types – Cambisols (CM), Fluvisols (FL) and Luvisols (LV). The highest mountainous parts are covered by Cambisols, which makes up 40 % of the area. Fluvisols are located in the lower parts of the area alongside Strumeshnitsa river. Luvisols are located predominantly in Ograzhden mountain. The vegetation in the study area is dominated by oak forests.

![Figure 1 Strumeshnitsa catchment in Bulgarian territory](image-url)
World Soil Database). ESDB provided information for the structure of the soils. HWSD was used as a data source for silt, clay and sand fraction, organic carbon and permeability class of the soils. A Digital Elevation Model (DEM) derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite sensor of 30 m spatial resolution was used to calculate the topographic factor (LS) of USLE. Landsat 5 TM image of 30 m resolution (path/row: 184/31) acquired on 15 July 2009 was used for calculation of C-factor.

2.3 Indicators

Appropriate indicators that represent quantitatively the processes by which ecosystems regulate water balance are needed in order to assess the capacity of ecosystems to mitigate soil erosion. In order to quantify the soil erosion regulation we use some USLE parameters. The Universal Soil Loss Equation (USLE) is the most widely used erosion equation. It is an erosion model designed to compute long-term average soil losses from sheet and rill erosion under specified conditions (Wischmeier and Smith, 1978).

The equation estimates soil erosion by six factors:

\[ A = RKLSCP \]

\( A \) - average annual soil loss (t/ha/year),
\( R \) - rainfall erosivity factor (MJ mm/ha h),
\( K \) - soil erodibility factor (t ha h/ha MJ mm),
\( L \) - slope length factor,
\( S \) - slope steepness factor,
\( C \) - cover-management factor
\( P \) - support practice factor

We estimate the supply capacity of erosion regulation ecosystem services based on four USLE factors that affect the rate of erosion – soil erodibility (K-factor), topographic factor (LS-factor), cover-management factor (C-factor). ArcGIS 10.1 (Figure. 2) was used to calculate the factors and estimate the capacity of erosion regulation ecosystem services.

![Conceptual scheme](image)

**Figure. 2 Conceptual scheme**

2.3.1 K-factor

Erodibility defines the resistance of the soil to both detachment and transport. Although a soil’s resistance to erosion depends in part on topographic position, slope steepness and the amount of disturbance, such as during tillage, the properties of the soil are the most important determinants. Erodibility varies with soil texture, aggregate stability, shear strength, infiltration capacity and organic and chemical content (Morgan, 2005). The main soil properties affecting K-factor are soil texture, organic matter, structure, and permeability of the soil profile. The physical, chemical, and mineralogical soil properties and their interactions that affect the value of the K-factor are many and varied. Several erosion mechanisms operate at the same time, each one relating differently to a specific soil property (Erkal and
Yuldirim, 2012). Usually a soil type becomes less erodible with decrease in silt fraction, regardless of whether the corresponding increase is in the sand fraction or the clay fraction (Wischmeier and Smith, 1978).

As direct measurements of K-factor on field plots are not financially sustainable at the regional or national levels, the soil erodibility nomograph is most commonly used and cited for soil erodibility calculation. An algebraic approximation of the nomograph that includes five soil parameters (texture, organic matter, coarse fragments, structure, and permeability) is proposed by Wischmeier and Smith (1978) Eq. (1) (Panagos et al., 2014):

\[ K = \left[ 2.1 \times 10^4 \left( 12 - OM \right) M^{1.14} + 3.25 \left( S - 2 \right) + 2.5 \left( P - 3 \right) \right] / 100 \]  

- \( M = (Si + VFS)(100 - CL) \)
- \( Si = \% \text{ Silt} \)
- \( VFS = \% \text{ Very Fine Sand} \)
- \( CL = \% \text{ Clay} \)
- \( OM = \% \text{ Organic Matter} \)
- \( S = \text{ Structure class} \)
- \( P = \text{ Permeability class} \)

Usually the sand fraction is categorised into five classes of sand: very fine, fine, medium, coarse, very coarse. The very fine sand structure (0.05–0.1 mm) as sub-factor (VFS) in Eq. (1) is not subject of standard soil analysis and was therefore estimated as 20 % of the sand fraction (Panagos et al., 2014). There is no data about organic matter, so organic matter is calculated by the Eq. (2) (Auerswad et al., 2014):

\[ \text{Organic Matter} \% = \text{Organic Carbon} \% \times 1.72 \]  

Table 1 Classes of soil structure derived from European Soil Database (Panagos et al., 2014)

<table>
<thead>
<tr>
<th>Code</th>
<th>Structure class (S)</th>
<th>European Soil Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(very fine granular: 1–2 mm)</td>
<td>G (good)</td>
</tr>
<tr>
<td>2</td>
<td>(fine granular: 2–5 mm)</td>
<td>N (normal)</td>
</tr>
<tr>
<td>3</td>
<td>(medium or coarse granular: 5–10 mm)</td>
<td>P (poor)</td>
</tr>
<tr>
<td>4</td>
<td>(blocky, platy or massive: &gt; 10 mm)</td>
<td>H (humic or peaty top soil)</td>
</tr>
</tbody>
</table>

Table 2. Soil permeability classes estimated from major soil textural classes (Panagos et al., 2014)

<table>
<thead>
<tr>
<th>Code</th>
<th>Permeability class (P)</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(fast and very fast)</td>
<td>Sand</td>
</tr>
<tr>
<td>2</td>
<td>(moderate fast)</td>
<td>Loamy sand, sandy loam</td>
</tr>
<tr>
<td>3</td>
<td>(moderate)</td>
<td>Loam, silty loam</td>
</tr>
<tr>
<td>4</td>
<td>(moderate low)</td>
<td>Sandy clay loam, clay loam</td>
</tr>
<tr>
<td>5</td>
<td>(slow)</td>
<td>Silty clay loam, sand clay</td>
</tr>
<tr>
<td>6</td>
<td>(very slow)</td>
<td>Silty clay, clay</td>
</tr>
</tbody>
</table>

2.3.2 LS-factor

Both the length (L) and the steepness (S) of the land slope substantially affect the rate of soil erosion by water. The two effects have been evaluated combined in this research. LS-factor is the expected ratio of soil loss per unit area from a field slope to that from a 22.1 meters length of uniform 9-percent (5.16°) slope under otherwise identical conditions (Wischmeier and Smith, 1978).
In the original version, slope length (L) was calculated either as the average horizontal distance from the source point and the point in which steepness (S) decreases and sedimentation begins, or where runoff becomes focused into a defined channel. This approximation works well in cultivated, flat or near-flat surfaces, but is not adapted to mountain regions (Pregnolato and D’Amico, 2011). Many methods have been proposed to improve the calculation of the topographic factor LS, but just in the last two decades a certain accuracy has been reached thanks to the implementation of GIS systems and of digital elevation model (DEM) (Bosco et al., 2009).

In this study we estimate the topographic factor with Eq. (3) (Moore et al., 1993):

\[
LS = (m + 1) \left( \frac{\lambda_A}{22.1} \right)^m \left( \frac{\sin(0.01745 \times \theta_{d,e} / 0.09)}{0.09} \right)^n 
\]

(3)

\( \lambda_A \) - the area of upland flow,
\( m \) - an adjustable value depending on the soil’s susceptibility to erosion,
22.1 - the unit plot length,
\( \theta \) - the slope in degrees,
0.09 - the slope gradient constant,
\( n \) - an adjustable value depending on the soil’s susceptibility to erosion

The LS factor is calculated in ArcGIS according to the following steps:

**Step 1. Filling the depressions**

The first requirement for the algorithm is a depressionless DEM. This is suggested for two reasons. First, true depressions are rare in nature, as such, depressions in DEMs are often errors. Second, depressions will return negative slope values. This will eventually result in negative erosion estimates (deposition) (Hickey, 2000).

**Step 2. Calculating Flow Direction**

The flow direction defines the flow path of water in areas adjacent to the lower altitude points in all of the positions in the hydrographic basin. Independent of the magnitude of the rain event, the flow algorithm in a GIS establishes a one dimensional flow network connecting each cell with other cells of the hydrographic basin in DEM until the point where the whole surface runoff generated inside the hydrographic basin meets, defined as the mouth. The estimate of the flow direction is based on the physical principle that the mass of controlled gravity proceed in the direction of the most accentuated slope (Oliveira et al., 2013).

**Step 3. Calculating Flow Accumulation**

The determination of the accumulated drainage areas (or accumulated flow), which allows the simulation of the hydrographic network, are defined based on the flow directions. The accumulated flow represents the amount of rain that will drain through each cell, supposing that all of the rain become torrents and there is no interception, evapotranspiration, or loss of underground water. Each pixel receives a value corresponding to the sum of the areas of all of the pixels whose drainage contributed to the analyzed pixel (Oliveira et al., 2013). The L-factor values are limited with the maximum value for slope length \( \lambda \), as suggested in the RUSLE user guide (1000 ft or approximately 300 m) (Pregnolato and D’Amico, 2011; Taveira-Pinto et al., 2009).

**Step 4. Calculating slope angle in degrees**

The slope is characterized identifying the plane tangent to the topographical surface in the centre of the cell. The maximum plane elevation change rate characterizes the inclination gradient, while the correspondent cardinal direction of this larger difference is the aspect (Oliveira et al., 2013). The estimation of LS is limited to a maximum slope angle of 50 % (26.6 degrees) (Panagos et al., 2015).

The values of exponents range for \( m = 0.2 – 0.6 \) and \( n = 1.0 – 1.3 \), where the lower values are used for prevailing sheet flow and higher values for prevailing rill flow. When nothing is known about the type of flow, \( m = 0.4 \) and \( n = 1.3 \) are usually used (Neteler and Mitasova, 2005).

**Step 5. Formula (3) is applied into Raster Calculator using the following expression:**
\[(1.4 \times (\text{Power}((\text{flowaccumulation} \times \text{cell size} / 22.1), 0.4)) \times (\text{Power}(\text{Sin}([\text{slope}] \times 0.01745) / 0.09, 1.3)))\]

### 2.3.3 C-factor

Factor C is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier and Smith, 1978). By definition, C = 1 under standard fallow conditions. As surface cover is added to the soil, the C factor value approaches zero. For example, a C factor of 0.20 signifies that 20% of the amount of erosion will occur compared to continuous fallow conditions (Kelsey and Johnson, 2003). Actual loss from the cropped field is usually much less than this amount. Just how much less depends on particular combination of cover, crop sequence, and management practices. It also depends on the particular stage of growth and development of the vegetation cover at the time of the rain (Wischmeier and Smith, 1978). The value of C-factor mainly depends on the vegetation’s cover percentage and growth stage. The effect of mulch cover, crop residues and tillage operations should also be accounted for in the C-factor (Van der Knijff et al., 2000).

Vegetation cover acts as a kind of buffer layer between the atmosphere and the soil. Leaves and stems as above-ground components of plants absorb some of the energy of raindrops and surface water. Below-ground components as the root system contribute to the mechanical strength of soil. Interception decreases the volume of rain reaching the soil surface. The effectiveness of the plant cover in reducing the raindrop impact depends on the height and the continuity of the canopy and the density of the ground cover (Erencin, 2000). The C-factor has been one of the most difficult USLE factors to estimate over broad geographic areas. Traditionally, spatial estimates of vegetation cover have been done by simply assigning values from literature or field data into a classified land cover map (Asis and Omasa, 2007). Different methods have been developed to improve C-factor mapping using remote sensing data. Several models using linear and non-linear regression were developed on the basis of the correlation between C-factor and vegetation indices, which, in turn, were obtained from satellite images to apply in soil erosion models (Anache et al., 2014).

Vegetation cover can be estimated using vegetation indices derived from satellite images. Vegetation indexes can delineate the distribution of vegetation and soil based on the characteristic reflectance patterns of green vegetation. The Normalized Difference Vegetation Index (NDVI), one of the vegetation indices, measures the amount of green vegetation. The spectral reflectance difference between Near Infrared (NIR) and red is used to calculate NDVI. The formula can be expressed as (4):

\[
\text{NDVI} = (\text{NIR} - \text{red}) / (\text{NIR} + \text{red})
\]

The NDVI has been used widely in remote sensing studies since its development. NDVI values range from -1.0 to 1.0, where higher values are for green vegetation and low values for other common surface materials. Bare soil is represented with NDVI values which are closest to 0 and water bodies are represented with negative NDVI values. (Patil and Sharma, 2013).

The Normalised Difference Vegetation Index is one of various mathematical combinations of satellite bands, which have been found to be sensitive indicators of the presence and condition of green vegetation. It is based on the reflectance properties of vegetation in comparison with water, snow and clouds on the one hand and rocks and bare soil on the other hand. Vegetated areas have high reflectance in the near infrared and low reflectance in the visible red. Water, snow and clouds have larger visual than near-infrared reflectance and bare soil and rocks have similar reflectance in both spectral regions. As a consequence green vegetation yields high values for the index, water has negative values and bare soil gives indices around 0 (Erencin, 2000).
The relationship between C-factor and NDVI can be established as (Figure 3). C-factor is calculated in Raster Calculator using this equation (5) (Lin et al., 2002):

\[ C = \frac{(1 - \text{NDVI})}{2} \quad (5) \]

3. RESULTS

3.1 USLE results

The values of K-factor range from 0.029 to 0.042 (Figure 4). The highest values indicate less resistance to soil erosion. With highest values (0.042) are the Fluvisols, situated alongside Strumeshnitsa river. Although most susceptible, they are located in areas with smaller gradients, which is a prerequisite for a lower degree of erosion. Following them are the Cambisols (0.035) occupying the highest parts of the study area. The most sustainable soils, with the lowest values, are Luvisols - 0.029.

The map of LS-factor confirms that mountainous parts of the watershed have the highest values. The highest value of the LS-factor is 31.98, with average value of 9.04. The average slope gradient is 14.7. About 30 % of the study area has high slope gradients - over 20 degrees, which are concentrated mainly in the southern parts. Areas with low altitude and slope gradients have low values.

The C-factor was derived from NDVI image of Landsat satellite data. The values of NDVI range between minus 0.25 and 0.80 with mean value of 0.52. The highest values are concentrated in the northern and southern parts where the forest vegetation is predominant. The values of the C-factor range of 0.09 to 0.62. The average is 0.23. High values indicate a greater risk of erosion. Soils without vegetation are represented with higher values.
3.2 Erosion regulation capacity of K-factor, LS-factor and C-factor

The capacities were assessed on a scale ranging from 0 to 5 (Table 3). A 0-value indicates that there is no relevant capacity to supply erosion regulation services and a 5-value indicates the highest relevant capacity for the supply of these services. Values of 2, 3 and 4 represent respective intermediate supply capacities. This scale offers an alternative relative evaluation scheme, avoiding the presentation of monetary or normative value-transfer results (Nedkov and Burkhard, 2012).

The K-factor is a measure of the inherent erodibility of a given soil under the standard condition of the USLE unit plot maintained in continuous fallow. Values for K-factor typically range from about 0.013 to 0.059 SI units, (0.10 to 0.45 US customary units) (McCool et al., 1995). Based on this assumption, we categorized the soils in five classes (Figure 5).

The LS-factor is limited to 300 m length and 26.6 degrees slope. So the values vary from 0 to 31.98. Those values are classified in equal intervals. A layer with slope steepness is reclassified with two values – 0 for slopes more than 26.6 degrees and 1 for slopes below 26.6 degrees. Both layers are multiple in Raster calculator, so the LS-factor capacity map gains 0 (no relevant capacity) value.

The C-factor ranges from almost 0 to 1. We divided 5 classes equally for the 1-5 capacity and only value 1 (soil without vegetation) will gain 0 capacity. It must be mentioned, that there is no real 0 value for vegetation cover. Even the densest vegetation cannot fully protect the soil.

<table>
<thead>
<tr>
<th>Ecosystem services capacity</th>
<th>K-factor capacity</th>
<th>LS-factor capacity</th>
<th>C-factor capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 = no relevant capacity</td>
<td>0.051 – 0.059</td>
<td>25.58 – 31.98</td>
<td>1 (soil without vegetation)</td>
</tr>
<tr>
<td>1 = low relevant capacity</td>
<td>0.042 – 0.050</td>
<td>19.19 – 25.58</td>
<td>0.80 – 0.99</td>
</tr>
<tr>
<td>2 = relevant capacity</td>
<td>0.031 – 0.041</td>
<td>12.79 – 19.19</td>
<td>0.60 – 0.79</td>
</tr>
<tr>
<td>3 = medium relevant capacity</td>
<td>0.022 – 0.030</td>
<td>6.39 – 12.79</td>
<td>0.40 – 0.59</td>
</tr>
<tr>
<td>4 = high relevant capacity</td>
<td>0.013 – 0.021</td>
<td>0 – 6.39</td>
<td>0.20 – 0.39</td>
</tr>
<tr>
<td>5 = very high relevant capacity</td>
<td>0 – 0.19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.3 Supply capacity of erosion regulation ecosystem service

The final output is obtained by summing the factors in Raster Calculator and divided by four, as LS-factor is used twice, because it contains two parameters – slope length and slope steepness:

\[
\frac{(K\text{-factor} + LS\text{-factor} + LS\text{-factor} + C\text{-factor})}{4}
\]

The result shows that the area has high erosion regulation capacity (Figure 6). The values range from 1.25 to 4.75. The mean value is 3.64. Those values are classified in equal intervals and equated to the main capacity classes - from 1 to 5 (Table. 3). With high capacity are the areas with low slope degree alongside the Strumeshnitsa river. The lowest capacity values are in the mountainous parts with steep slopes. There are only few areas with low relevant capacity, because in the mountains there is good vegetation cover, which moderate the values.
3.4 Limitations

The limitation of the USLE factors maps is that each morphological unit is assumed to be homogenous. In raster data each grid cell has a single value. This means, that every value is concerned to pixel size 30 x 30 m, so heterogeneity within each pixel is ignored. The main source of error is likely from C-factor values that were estimated from satellite image. Estimation C-factor with NDVI analysis is alternative method, which shows approximation values. It does not precisely reflect the protective cover against soil erosion. The satellite image is from 2009 year, so there may be changes of vegetation cover. Also in different vegetation period will show different values. The soil data could have more soil classes. The assessment could be improved by higher spatial resolution and including recently acquired images from different periods.

4. CONCLUSION

The methods used in this article made some assumptions, which will affect the accuracy of the results. Therefore, these results should be interpreted with caution. Using non-monetary method for estimation can’t show precise measurement, but can provide useful information for ecosystem services supply. The results show that GIS and remote sensing data can be a valuable tool in mapping ecosystem services. Mapping ecosystem services is valuable for understanding the relationship between land characteristics and their services. With improved methodology and data, the model can provide various scenarios of the land characteristics effect on ecosystem services supply in different scales.

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Stoyan Nedkov is Assoc. Professor in the National Institute of Geophysics, Geodesy and Geography at Bulgarian Academy of Sciences. His research area is landscape ecology and application of GIS in environmental assessment. His current work is focused on assessment and accounting of ecosystem services at landscape level as well as use of GIS and spatial modeling for integrated assessment of hazardous processes in mountain catchments and mapping of flood regulation ecosystem services. Dr. Nedkov has more than 50 publications in different journals and books and was a guest editor in international journals Ecosystem Services and Ecological indicators. S. Nedkov had lectures at Salzburg University (Austria) and University of Joensuu (Finland). He is member of the Steering Committee of the Ecosystem Services Partnership.

Boris Markov is graduated in “GIS and cartography” from Sofia University “St. Kliment Ohridski”. Now he is PhD student. His research interests are GIS, remote sensing, natural resources management.