Proposal to support:

Characterisation of Waste Sites Along the Lim River in Serbia

Final Report

Support requested by:
United Nations Development Programme (UNDP)

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1 DEVELOPMENT CONTEXT AND BACKGROUND

It is a reality that the increasing volume of waste generated by mankind and its disposal present a global problem to our environment. Agenda 21 programme of United Nations (https://sustainabledevelopment.un.org/outcomedocuments/agenda21) defines the action plan with regard to sustainable development of countries. Particularly, chapters 20 and 21 of the document are devoted to promoting the reduction, management and recycling of hazardous and non-hazardous wastes. Moreover, the European Union has been quite active in the introduction measures to prevent waste and its safe disposal. Indeed, Directive 2006/12/EC of 5th April 2006 on waste creates a framework for the management of all waste streams within the European Community. This framework requires that Member States implement measures which control the recovery and disposal of waste, and it also requests Member States to draw up and adopt plans for the management of waste. The core provisions of the Directive direct the Member States to:

- Article 4(1) Directive 2006/12/EC – "Take the necessary measures to ensure that waste is recovered and disposed of without endangering human health and without using processes which could harm the environment";
- Article 4(1) Directive 2006/12/EC – "Take the necessary measures to prohibit the abandonment, dumping or uncontrolled disposal of waste";
- Article 5(1) Directive 2006/12/EC – "Cooperate in the establishment of 'an integrated and adequate network of disposal installations";
- Article 13 Directive 2006/12/EC – "Require establishments or undertakings which collect or transport waste on a professional basis or which arrange for the disposal or recovery of waste on behalf of others to be registered with the competent authorities were not already subject to authorisation";

Under the regulatory framework defined by European Commission, Serbia needs to take measures and activities into the proper management of waste and its disposal.

The use of space-borne remote sensing technology to support waste management, and particularly to control the disposal of waste has been explored in many research projects over the last thirty years (Ottavianelli et al. 2005 [12]) However, most of the studies found the limitations of using low-resolution imagery from SPOT and Lansat missions. Those limitations are avoided by using newer sensors such as Pleiades, or WorldView, which provide resolutions below the meter. We thus firmly believe that the scope of this project will assist the Serbian government in achieving its objectives and towards its future adhesion into the EU. Indeed, remote sensing can be applied for performing current analysis of waste disposal, and to develop a methodology for monitoring of disposal sites, and subsequently control illegal dumping that may lead to sanitary and economic issues. Surely, the methodology described herein may serve as a starting point for a larger project aligned with the positive objectives of the Serbian government and most importantly the environment.

2 OBJECTIVES, WORK LOGIC AND EXPECTED OUTPUTS

2.1 Work Order Objectives.

In its request for proposals, the United Nations Development Program (UNDP) expresses its need for the development of a methodology for the mapping and characterisation of waste disposal sites located along shores of the Lim River in Serbia. Although developed with a local case (the Lim River), the UNDP hopes to use the methodology in other areas of Serbia (e.g. Drina River) and surrounding states. The following requirements in the development of the methodology have been specified:

1. **Legal as well as illegal waste disposal sites must be mapped**

This means that the proposed methodology must be able to map known as well as unknown waste disposal sites. The methodology cannot solely rely on existing location records. It must be able to find unrecorded sites. Section 2.3.3. of this document the service describes the methodology to extract the waste disposal sites. A first approach to the methods for checking the thematic accuracy is also described in case of absence of ground truth data.

2. **The work must be based on very high resolution (VHR) optical imagery**

The main source of information for the detection and mapping of the waste disposal sites will be EO imagery. We agree that only VHR imagery will allow for the distinction of waste disposal sites from other types of open and non-vegetated sites (e.g. commercial and industrial yards). Moreover, we think that a minimal image resolution of 1 m (or less) is necessary. Satellite imagery can offer such a resolution and it can cover large areas for a reasonable price. A first analysis of the imagery availability over the AoI was carried out and is documented in section 3 of this document "Data Availability and Procurement".

3. **The mapping date must be as recent as possible**

The UNDP supports the Serbian Ministry of Environmental Protection in its effort to address the problem of water pollution associated with inadequate waste management. Their actions must be based on up-to-date information. Consequently, the EO imagery to be used must be recent, ideally acquired in the last year.

As explained in section 3 of this document, the data availability is limited, due to cloud cover, snow, and other factors. However, an analysis of data acquired by various satellite missions over the area lead to the conclusion that the most suitable imagery for the project comes from the Pleiades constellation and was acquired in 2019.

4. **The proposed method must be automatic or semi-automatic**

Waste disposal sites can be of variable sizes, be found in a variety of environments and change over time. Furthermore, their mapping requires the analysis of large territories. The automation of the mapping process will facilitate its repeated application over space (different areas) and time (different years). It will also standardize the mapping results. This is important for comparative studies and monitoring activities. Sections 2.3.3.2 and section 2.3.4.2 describe the methodology for the services execution. The reader will find that the method is based on AI-based data exploration, which ensures efficiency and reliable results extraction. This highly automated method will serve well on a future standardization of monitoring of waste disposal sites.

5. **The area to be mapped consists of a 500 m band of land on either side of the section of the Lim river that is situated in Serbia**

Although the mapping of waste disposal sites is restricted to this area, it might be necessary to acquire EO imagery in a larger area (or other areas) in order to collect a sufficient number of training sites necessary for the automatic mapping method. Indeed, the services that will be executed under the scope of this contract will be limited to the AoI indicated on the Work Order Tender document. However, the methodology described herein could be extended to a wider area. To ensure that the training of the NN used is robust, sufficient data sets from other areas out of the indicated AoI needs to be used.

2.2 Work Logic.

The work logic of this particular Work Order has been defined to ensure the provision of an efficient service to UNDP and ESA, maximizing added value outputs, delivered on time and in the required format. Indeed, the work for this RFP is organized around five work packages (WP).

- **WP0**: the overall management and the successful implementation of the work as well as the delivery of the results. (everis)
- **WP1**: This working package is focused on the imagery's acquisition, preparation, and pre-processing of the imagery data. (Effigis)
- **WP2**: This working package includes the AI-based mapping of disposal waste sites along the section of the Lim River that is situated on the territory of Serbia. (Effigis)
- **WP3**: This working package includes the identification and characterization of potential environmental harms to watercourses related to the waste along the AoI. (I-Sea)
- **WP4**: This working package contains the final report, recommendations, technical verification and quality assurance of the results of WP 1, 2 and 3. (Everis)

The high level work logic is described in the following Figure 1:

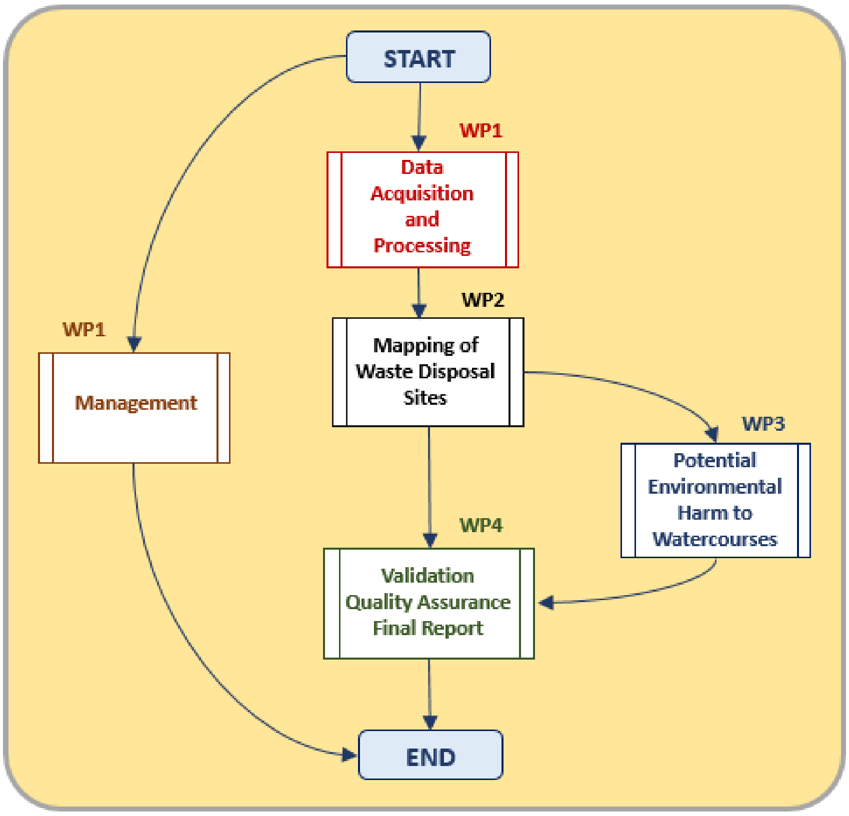


Figure 1 Work Logic of Work Order

2.3 Description of Work packages.

2.3.1 WP0 - Management.

Management activities of this project were performed by everis. Management processes followed the ones described in reference Management Proposal. In this proposal, only specific management aspects for this RFP are described. In order to control the progress of the work order with respect to cost, schedule and technical objectives, the following milestones were set up:

Milestones		Date
Kick-off Meeting (KOM)	Once the Work Order (WO) was launched, a KOM was to be held by ESA, UNDP Serbia and Everis to review schedule, scope of the work and deliverables. It was agreed the mobilization of UNDP Serbia local staff to provide logistics support for the execution of WO and the potential integration with GeSrbija, the official geospatial platform of Serbian Re-public Geodetic Authority (RGA).	T0
Acceptance Review	A final meeting with ESA, UNDP Serbia and Everis will be performed to review and accept the work done along the work order.	T0+4w

Table 1. Milestones management.

Other management-related tasks such as cost control procedures, progress reporting, meetings management, actions management and so on will be carried out as stated in Management Proposal. Moreover, the proposal manager will contribute to the final report with the conclusions obtained during the Work Order, and related to the estimation of feasibility, conditions and cost of an extended service.

2.3.2 WP1- Data acquisition and pre-processing.

2.3.2.1 Objectives and tasks

Task 1.1 - To retrieve additional input data to include it into the working flow and services methodology:

The objective of Work Package 1 (WP1) was to acquire and pre-process the data that was going to be used for the mapping of the waste disposal sites. A quick research on the topic of waste disposal sites in Serbia had identified another data set that was to be useful in the development of the mapping methodology. This data set was the inventory of active and old landfill and dumping sites in Serbia, available from the Serbian Environmental Agency (SEPA). This inventory was compiled by (Stanisavljevic et al. 2012 [13]) through interviews with municipal waste management officers. Therefore a first task of investigating and collecting additional datasets, such as the one compiled by (Stanisavljevic et al. 2012 [13]), was included in the work flow. The idea was that these additional datasets would help to streamline the services.

Task 1.2 - To contact involved stakeholders that may provide valuable input data:

The main data source used for the mapping was EO imagery. In its request for proposals, the UNDP stated that orthophotos of the area of interest could be made available from GeoSrbija. The second task of WP1 was to contact GeoSrbija and inquire about the availability and possible use of their EO imagery. A visit to their website (https://a3.geosrbija.rs) suggested, however, that their most recent imagery dated to 2015 or 2016. Although this imagery was not recent enough for the production of an up-to-date map, it was deemed useful for collecting training data.

Task 1.3 –First inventory of VHR satellite imagery:

Task 3 of WP1 was to update the inventory (see section 3) of the most recent VHR satellite imagery (1 m or less) that was available in the imagery archives.

Task 1.4 – Procurement of selected EO imagery:

Task 4 of WP1 was the selection and purchasing of the most appropriate EO imagery to be used for the mapping of the waste disposal sites. As previously mentioned, an automatic or semi-automatic mapping methodology was proposed. This required the collection and use of a large number of training sites. We thought it necessary to collect some training sites outside of the principal area of interest (Lim River).

Task 1.5 – Selection of other known waste site areas, and acquire imagery to feed the trainer of AI-Algorithm:
Task 5 of WP1 was to analyse the SEPA database and identify other areas that could be used for the collection of training sites. This analysis took into account the availability of secondary EO data (from GeoSrbija).

Task 1.6 – Acquired data pre-processing and organization for its analysis:
Once all the required EO imagery had been acquired, task 6 of WP1 was to pre-process it so that it could be properly used in the mapping procedure. Usual pre-processing tasks included performing atmospheric and radiometric corrections as well as performing geometric corrections. Atmospheric and radiometric corrections are necessary to optimize and standardize the calculation of ground reflectance. A standardized ground reflectance was necessary for the development of mapping methods based on spectral signatures and for the repeatability (in space and time) of the methodology. Geometric corrections (orthorectification) were necessary to guarantee a minimal spatial accuracy for the imagery that was used for the mapping of the waste disposal sites.

2.3.2.2 Processing methodology and elaboration of data layers

The methodology of the first work package was therefore aligned with the tasks described in the previous section.

A. We received a recent inventory of waste disposal sites in the Lim river area from the Department of Environment Protection.

B. We retrieved the waste disposal sites database from the Serbian Environmental Protection Agency website (http://www.sepa.gov.rs/) and converted it into a cartographic data layer (shapefile).

C. We made an inventory of the most recent VHR satellite imagery available in archives.

D. We selected and purchased 2019 Pleiades satellite imagery for an up-to-date mapping of waste disposal sites in the principal area of interest (Lim River – about 100 km^2).

E. We pre-processed the acquired satellite imagery
   i. Atmospheric and radiometric corrections: we purchased already corrected Pleiades imagery therefore no atmospheric or radiometric corrections were necessary.
   ii. Orthorectification: the purchased images were geometrically corrected in order to guarantee minimal spatial accuracy. Orthorectification was performed using the PCI Geomatica software[1]. Available orthophotos were used to extract ground control data (GCP points) and the SRTM 30-m DEM was used for the orthorectification of the 2019 Pleiades images.
   iii. Mosaicking: More than one image was necessary to cover the area of interest. In order to facilitate the mapping process, these images were assembled into a single image mosaic. We used the PCI Geomatica software to perform the image mosaicking.

F. We analysed the SEPA waste disposal sites database to identify possible secondary areas for collection of training sites.

G. We obtained an authorization from the Republic Geodetic Authority (RGA) for the retrieval and use of archive orthophotos (RGB) covering the identified secondary areas.

2.3.2.3 Outputs

The main outputs from WP1 were:

(1) 2019 ortho-mosaic upon which the map of the waste disposal sites was based;

[1] PCI Geomatica is a remote sensing desktop software package for processing earth observation data, designed by PCI Geomatics

(2) A geodatabase of the inventoried waste disposal sites (SEPA) to be used for the collection and characterization of training sites;

(3) Orthophotos to be used for the collection of additional training.

2.3.3 WP2 – Main Service - Automated mapping of waste disposal sites along the Lim River

2.3.3.1 Objectives and tasks.

The main objective of Work Package 2 (WP2) was to develop an automated methodology for the mapping of waste disposal sites.

Task 2.1 – Waste site characterization:
The first task of WP2 was the production of an interpretation guide for the identification of waste disposal sites on EO imagery.

Task 2.2 – Training and validation data sets creation:
The methodology proposed for the automated mapping of waste disposal sites was the use of a supervised classification approach. A first classification would be based on the recognition of the spectral signatures of different land cover classes. It would be followed by a second classification that would be based on the recognition of image patterns associated with waste disposal sites (deep learning). Both of these approaches required the use of training sites.

The second task of WP2 was therefore to create training and validation data sets. They would be identified with the combined use of the SEPA geodatabase and the examination of the VHR imagery (recent and old).

Task 2.3 – Segmentation and pre-classification of open non-vegetated areas using the recognition of spectral signatures
Task 3 of WP2 was the creation of a set of objects that would be submitted to the supervised classification. The objective of this task was to limit the number of classes that would need to be recognized by the AI-based classifier. In order to do so, the objects derived from the segmentation of the 2019 orthomosaic were submitted to a pre-classification that identified the open non-vegetated areas (including the waste disposal sites). This supervised classification was based on the recognition of spectral signatures.

Task 2.4 – Waste disposal sites classification
Task 2.4 was to submit the objects associated with open non-vegetated areas to a AI-based classifier and identify the open non-vegetated areas corresponding to waste disposal sites.

Task 2.5 – Validation of output data and quality assessment:
Finally, task 2.5 consisted in the calculation of the mapping success and error rates obtained using a validation data set. This validation data set was created by visually sweeping the entire AOI and photo-interpreting the existing waste disposal sites on the 2019 Pleiades imagery.

2.3.3.2 Processing Methodology and elaboration of data layers

A. We produced an interpretation guide for the identification of waste disposal sites. The interpretation guide described key characteristics associated with waste disposal sites. Four types (classes) of waste disposal sites were defined: exposed waste, buried waste, levelled waste, and industrial waste.

B. We collected training and validation sites on VHR images.

    i. Training sites (image clips) were collected from the archive orthophotos provided by the RGA. The 2012 SEPA inventory was used to locate waste disposal sites whose presence was confirmed by visual inspection of the archive orthophotos taken between 2007 and 2013. Nearly

450 training sites were collected from these archive orthophotos (RGB): 413 exposed waste sites, 27 buried waste sites, 20 levelled waste sites, and 37 industrial waste sites. The training image clips were extracted from the orthophotos resampled at a 50-cm resolution (same resolution as the 2019 Pleiades orthomosaic).

ii. An up-to-date inventory of the waste disposal sites present in the Lim river AOI was carried out through a systematic visual inspection of the 2019 Pleiades satellite image mosaic. Site location and perimeter were manually mapped in a GIS. This 2019 manual inventory was considered as the reference dataset to be used for the validation of the results obtained with the automated detection of waste disposal sites.

C. We created the objects to be classified with AI

i. The 2019 Pleiades orthomosaic was segmented (multiresolution segmentation) over the entire area of interest.

ii. The resulting objects were pre-classified into main land cover classes

- Water
- Vegetated area (Forest, Agriculture)
- Open non-vegetated area (built-up area, roads, mineral surfaces, including waste disposal sites).

This pre-classification was based on the recognition of the spectral signature associated with each class. The supervised classification included a Nearest-Neighbour classification combined with a threshold-based decision tree.

iii. The objects pre-classified as open non-vegetated areas were assembled into a dataset to be subjected to the AI-based classification.

The segmentation and pre-classification were performed using the eCognition Developer software.

D. We performed an AI-based classification of the open non-vegetated areas

i. Selection of an initial set of classification model parameters (size of analysis window, number of training sites per class)

ii. Initial AI-based classification of open non-vegetated areas

iii. Optimization of model parameters (and improvement of training set by integration of classification errors (learning loop)

iv. Final AI-based classification of open non-vegetated areas

v. Map of waste disposal sites along the Lim River

The ResNet deep learning neural network algorithm was used for the AI-based classification. It was trained with the image clips extracted in task 2.2 (training set from the 2007-2013 image clips).

E. We assessed the accuracy of the map produced with the AI-based classification. The validation dataset was used to calculate Producer's accuracy (omission errors) and User's accuracy (commission errors).

2.3.3.3 Outputs.

The main outputs consist of:

(1) Reference map of waste sites

- Cartographic map layer (shapefile) of all the waste disposal sites photo-interpreted from the 2019 Pleiades orthomosaic. It is the dataset used for the assessment of the potential environmental harm to watercourses (WP3) and it will also be integrated into the GeoSrbija database.

(2) Map of waste sites detected with the AI-based classification:

- Cartographic map layer (shapefile) of all the waste disposal sites detected by the AI-based classification. This cartographic layer (shapefile) consists of the outlines (polygons) of the waste disposal sites detected by the AI-based classification.

(3) Map accuracy assessment based on with mapping success rates, including omission errors (false-negatives) and commission errors (false-positives).

2.3.4 WP3 – Potential environmental harm to watercourses related to the waste – Impact.

Landfills can potentially pose major hazard to the environment, even in the case of sealed waste dumps (Brito et al., 2014 [2]). Organic and inorganic contamination or pollution due to heavy metals can impact soil and aquifers but can also threaten the rivers when waste dumps are found along riverbanks. In this case, inflow of effluents together with large solid waste can impact river water quality. Floods runoff and riverbank erosion are processes contributing to the generation of large amounts of solid wastes in rivers (e.g. Zafar and Alappat, 2004 [15]) that lead to the accumulation of large amounts of waste in the seas and oceans (Jambeck et al., 2015 [8]). Also, (Lella et al. 2017 [9]) have demonstrated that the vegetation cover changes at a depletion rate of 2100 square metre area in and around dumping sites. As a negative feedback, the destruction of natural vegetation will enhance soil and riverbank erosion since riparian buffers have a significant impact on stream bank stabilization (Thomson et al., 2004 [14]; Hughes, 2016 [7]). Therefore, landfills located along riverbanks are also expected to increase the release of sediments to watercourses involving potential negative impacts to the environment and human activities (e.g. sustaining water resource security, as underlined by Chen et al., 2013 [3]). Also, increased riverbank erosion will, with time, directly connect the waste disposals to the watercourse.

HR and VHR satellite remote sensing allows us to focus on various aspects of the potential harmful impacts of the landfills. We propose to focus on three main aspects:

- The introduction of solid macro-waste into the rivers,
- The introduction of optically detectable organic / inorganic effluents into the watercourse,
- The risk of riverbank erosion in the vicinity of landfills,

Since these impacts are theoretical, independent experiments will be carried out. Results and perspectives will be clearly provided in the project report, highly valuable information that stakeholders can use in further analysis. The selection of the experiments to carry out will be proposed at the Kick of Meeting of the Work Order, and those will be discussed and agreed with UNDP according to their priorities.

2.3.4.1 Objectives and tasks.

WP3 may be decomposed into three objectives:

- The **first objective** – will be the identification of solid macro-wastes in VHR images acquired for the study and evidence of the potential of automated image analyses for counting and locating solid macro-waste in the study area,
- The **second objective** – will be the identification of water colour anomalies in the vicinity of the landfills and computation of the turbidity generated by dumping areas,
- Finally, the **third objective** – will be the identification of riverbank erosion that may be worsened by vegetation cover degradation in dumping areas and that may induce increased risk of water pollution (riverbank destruction and garbage release to river course).

To achieve the objectives, following tasks are identified:

- Task 3.1 will be focused on the photo-interpretation of VHR imagery to identify and locate macro-wastes. It will take as an input the outputs generated in WP 1 described in section 2.3.2.
- Task 3.2 consists in the analysis of the water colour changes in areas surrounding landfills.
- Finally, task 3.3 consists in the riverbank 2D-morphological analysis.

Tasks identified above will be supported by the processing methodology and methodology defined in next section 2.3.4.2 of this document.

2.3.4.2 Processing Methodology and elaboration of data layers.

2.3.4.2.1 Macro-waste detection

Macro-waste automated detection could be achievable using deep-learning approach. With this aim, deep models must be trained with important image databases representing a variety of garbage in a variety of rivers and watersheds. Keeping in mind the final objective of an automated detection of macro-wastes in Serbian rivers, our first attempt, during the present study, will be to start collecting a training dataset, and, therefore, to collect the location of all observable waste in the watercourses.

With this aim, an image interpretation procedure will be applied. Satellite images delivered by WP 1 have been analysed by a single photo-interpreter working with QGIS.

Three Pleiades images were processed, recorded on November 6th 2018, July 4th 2018 and August 8th 2019. Image resolution is of 50 cm. The image mosaic covers the whole Lim river (Figure 2).

The analysis strategy is described in Figure 3.

First, the images have checked to mask out any sections not exploitable. Three main parameters can influence the identification of objects at the water surface that are, namely, the sun glint, the turbulence and the shadow (of cliffs in the context of the Lim River). Exploitable and masked sections have been contoured and a shape a been created based on the generated polygons.

Second, all floating devices are collected. Due to the image resolution, the accurate identification of the wastes is not achievable. Consequently, we have decided to attribute to each detected floating object a confidence level[1]. The confidence level has been attributed on a set of criteria defined on the Pleaides data and also on all images available in Google Earth. A confidence level 50% has been attributed to small objects (1 to 2 pixels in length) visible only in Pleiades images (i.e. never visible in Google Earth). A confidence level 25% has been attributed to big objects (more than 2 pixels in length) visible only in Pleiades images. Finally, a confidence level of 10% has been attributed to sectors were water aspect seems to reveal floating devices, although individual objects are not clearly observed. Observation are located away from turbulence or glint areas (either on Pleiades or Google Earth imageries) but have the appearance of one of these phenomena. The highest confidence level is therefore 50%, since we can nether certify the origin (either anthropogenic of natural) of the floating object.

In order to take full advantage of the data collected and to benefit from wate site identification, a joint-analysis of the detected wastes and dumping areas has been finally performed, in order to search for spatial correlations between garbage observations in the river and existing dumping site at a distance varying from 200 meters to 500 hundreds of meters. With this aim buried areas have been classified as a function of their capacity to export rubbishes to the Lim River.

[1] Please note that there is no Deep learning used to derive waste location. This project is a test to check the concept: so only using direct observation from the image. Therefore, the confidence level used is adapted to this test. If the concept is finally to be adopted in a bigger project, then, a big training dataset would be compiled to train Deep learning algo to automatically detect the wastes and attribute an automated confidence level.

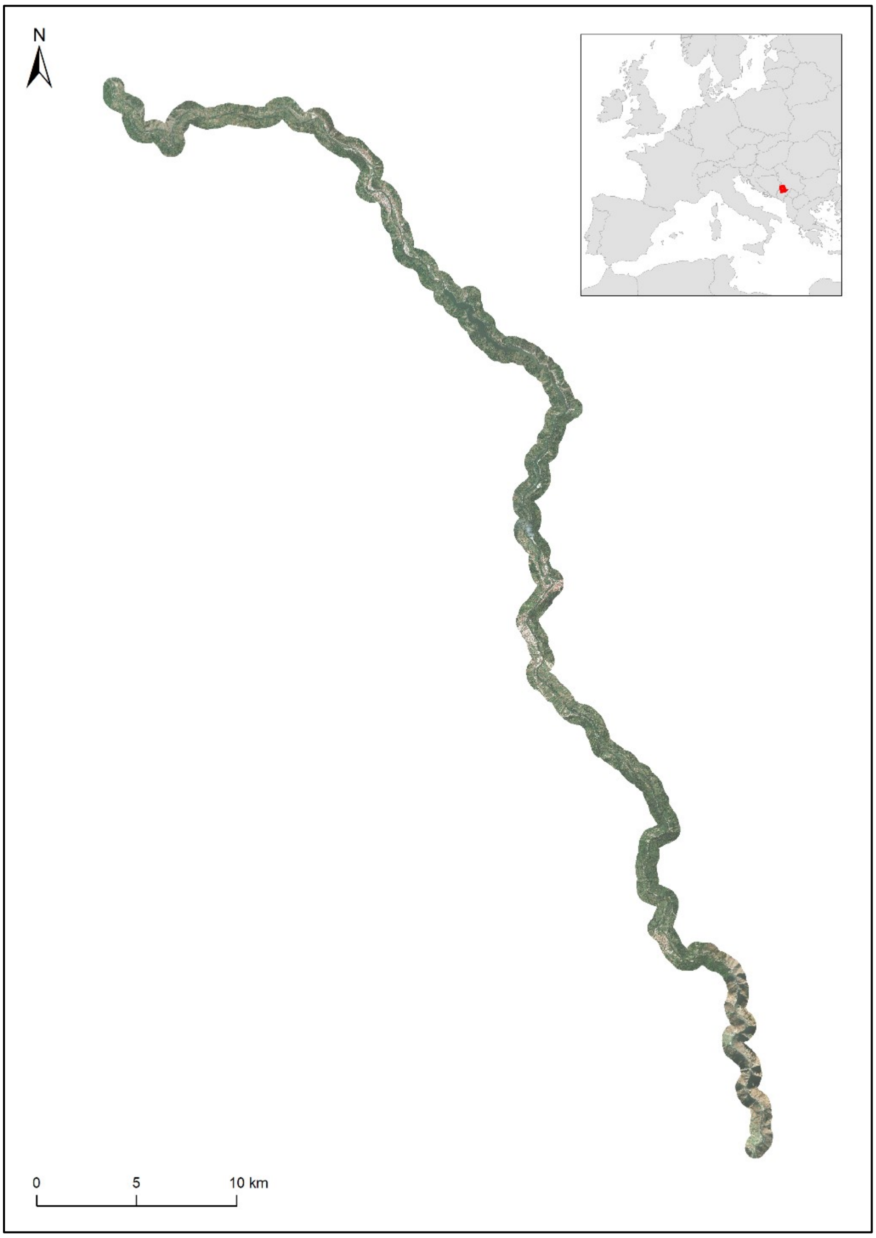


Figure 2 Pleiades mosaic used to derive solid wastes

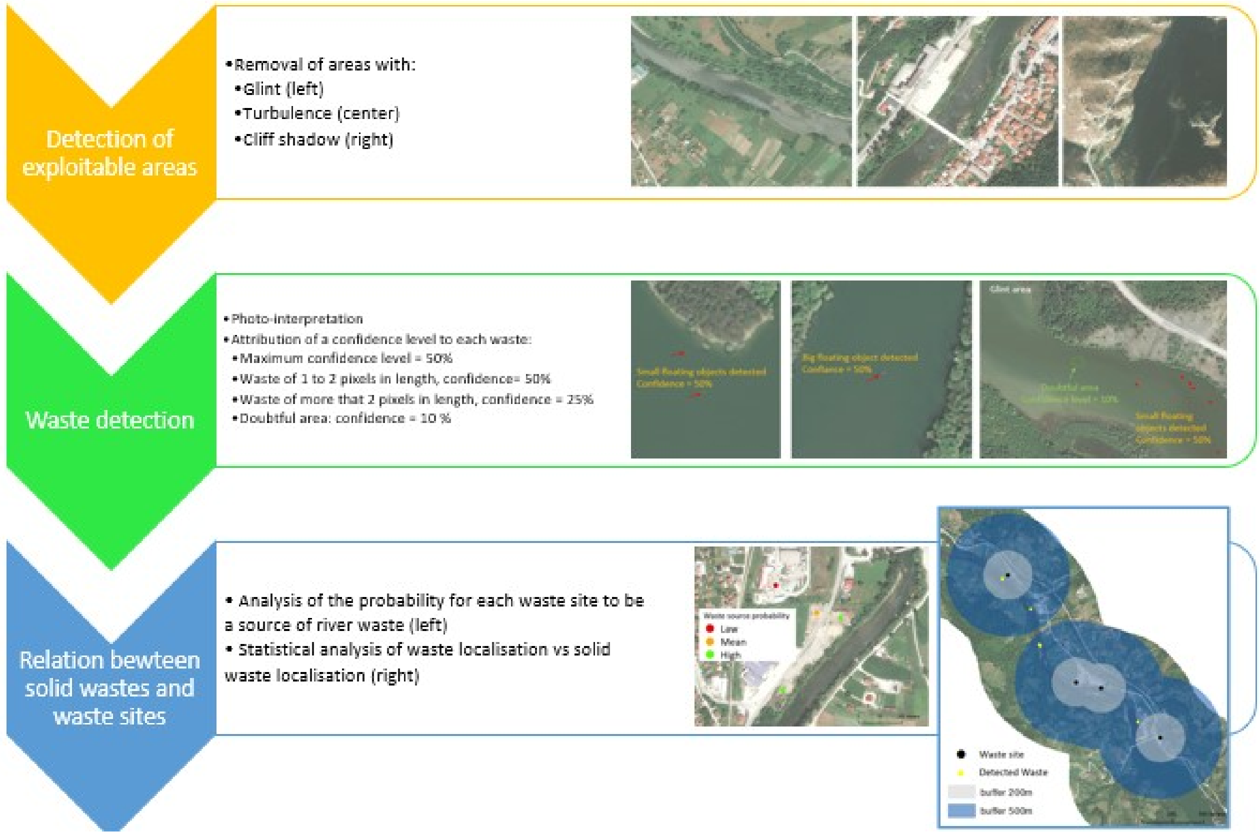


Figure 3 *Analysis strategy to derive the potential impact of waste site on waste distribution along the Lim River*

The following criteria have been specifically considered for this project, in order to classify the landfills:

- High probability to be a waste source to the river: the landfill is located less than 30 m from the riverbank
- Medium probability to be a waste source to the river: the landfill is located at a distance ranging from 30 to 150 m from the riverbank and is not separated from the river by roads, railways or buildings, or the landfill is located at 30 m to 80 m from the river and a road is observed between the buried area and the river.

Medium probability to be a waste source to the river: the distance between the waste site and the river exceeds 80m and a road, railway or buildings separate them.

2.3.4.2.2 Identification of organic / non organic particles and or/dissolved matter in the vicinity of landfills.

To achieve this task, the location of landfills in the vicinity of riverbanks is required. Then, it will be also necessary to be informed about the period in which the dumping area was first observed. Thus, this task will rely on the output of WP 2, and will focus on the vicinity of the sites detected by this WP.

In order to identify the potential impact of landfills on the water column, either due to the presence of organic/inorganic particulate/dissolved matter, it is necessary to use long series of images. As a natural process, water colour changes with time, with e.g. change in river runoff, input from tributaries bearing drain-age from disturbed areas uphill. In rivers, water can suddenly change from green related to photosynthetic activity to brownish/reddish tones when clays are observed. Therefore, natural colour conditions must be carefully studied in order to highlight changes in the natural trends. In rapid watercourses, as the ones currently studied, we don't expect many changes. So, we make the hypothesis that a fast analysis of water colour changes, based on two years of HR data will be sufficient. In any case, VHR imagery is not sufficient for this analysis.

First, a database of cloudless/snowless Sentinel-2 images (level L2A) available on the area is constituted. In each image, every water pixel is converted to SPM concentration using a semi-analytical generic algorithm (Nechad *et al.*, 2010 [10]) .

Second, a transect line shapefile is drawn all along the Lim river passing approximately in the middle of the river. This transect is further cut into a series of smaller transects of approximately 500m long. Any manmade (bridges, dams, etc.) or natural (banks, etc.) structures are excluded from the transects to focus only on pure water pixels.

Third, for each Sentinel-2 image of the database, the SPM values of pixels intersected by each transect is retrieved and averaged. This operation creates a temporal database of average SPM concentrations for each transect along the Lim river. This database is further statistically analysed to detect temporal anomalies

The procedure developed is based on a four-step process:

- First, a two-year database of cloudless/snowless Sentinel-2 images available on the area is constituted. In each image, every water pixel is converted to SPM concentration using a semi-analytical generic algorithm (Nechad *et al.*, 2010 [10]),
- Second, using a transect line shapefile drawn all along the Lim river passing approximately in the middle of the river, SPM values are extracted from each Sentinel-2 data and averaged along 500 m long sub-transects. Any manmade (bridges, dams, etc.) or natural (banks, etc.) structures are excluded from these sub-transects to focus only on pure water pixels,
- Third, this temporal database of average SPM concentrations for each transect along the Lim river is further statistically analysed to detect temporal anomalies: mean SPM (Mean_SPM) and SPM standard deviation (STD_SPM) values are computed over the entire time series for each transect. If an SPM value is higher than Mean_SPM + 2.5 * SPM_STD, it is considered as an anomaly;
- Finally, the detected anomalies are compared with locations of detected landfills, either in the vicinity of anomalies or further upstream, to investigate if they could be related.

The identification of organic / non organic particles and/or dissolved matter in the vicinity of landfills is valuable to assess the potential impact of landfill creation on the water column since uncontrolled input may contaminate the water from short to long-term time ranges and also from local sale to downstream watershed.

2.3.4.2.3 Evidence of erosion in the sector of dumping areas.

A 2D-analysis of the riverbank morphology will be undertaken, in order to derive erosion trends over the past 5 years to assess erosion risk in the vicinity of landfills. With this aim, diachronic analysis must be carried out. In order to perform this analysis, we will consider a pair of very-high resolution images.

A two-step procedure will be applied:

- First, we will derive erosion trends all along the study area,
- Second, riverbank changes will be overlaid onto the landfill location map delivered by WP2 in order to determine whether landfills play a significant role in riverbank erosion and identify to ones presenting current major erosion risk.

Two dates among the available airborne images and VHR data delivered by WP 1 will be used. The data set for year 2009 will not be used as the river was at low water due to a dam regulation (the position of the banks does not reflect the long-term trend but a one-time position not comparable with the other dates).

From each image used for this study, waterlines will be extracted (Alicandro et al., 2019 [1]) by photointerpretation and compared using the Baseline method (e.g. Himmelstoss et al., 2018 [6]). Profiles perpendicular to the banks are created every 50-m long. The position of the riverbanks is quantitatively compared between the two dates and statistically estimated in m/yr.

A 2D projection of erosion trends will be carried out in order to model the location of the riverbank location in a near future (2030 and 2040). This task will be carried out for the right bank as a representative example. These modelled riverbank locations will be superimposed on the landfill map obtained from WP 2. Then, an automated alert analysis will be implemented to highlight the areas where erosion will reach the waste disposal and under what time horizon.

Then, a spatial analysis will be implemented to highlight the eroding areas close to the landfills.

2.3.4.3 Outputs.

With regards to solid waste detection, main outputs will consist of:

- GIS layers displaying solid-waste location. One layer per inspection date will be provided, multi-detection of the same objects will be removed,
- A technical report:

In the final Work Order report that compiles findings and conclusions, the following information coming from this WP will be included:

- o Reporting of the location of the detected wastes in comparison to landfill location,
- o Detailing the potential and limits of VHR image analysis to control macro-waste production in larger scale watersheds.

With regards to identification of organic / non organic particles and or/dissolved matter in the water column, the outputs will consist of:

- A section of the technical report documenting the potential impact of dumping areas on terrigenous and/or effluents of alternative origin on the water column,
- GIS layers showing the amplitude of the impact in terms of relative quantity of particulate/ dissolved matters identified and area of influence along the watercourse.

With regards to demonstrating the existence of riverbank erosion, the main outputs will consist of GIS layers showing riverbank location with time and identifying as polygons, significant changes with regards to detection method accuracy (usually of the order of the image spatial resolution). Then, indication of major risk of erosion of riverbanks connected to landfills.

All the output GIS layers will be provided using standard raster or vector formats easy to integrate into the end user GIS Server. If necessary, a customized Web GIS server may be deployed to show the generated information layers.

2.3.5 WP4 - Technical Verification, Quality Assurance, and Final Report Creation

2.3.5.1 Objectives and tasks.

Main objectives of the WP4 will be dedicated to ensure the overall quality of the service and report findings and conclusions acquired during the WO execution. An independent technical verification will be performed over the generated outputs. Moreover, quality assurance principles such as those described in the management section of the management proposal will be followed. Those procedures will be tailored to fit into the 4-week time frame, and then ensuring that a minimum quality is reached.

The second objective of WP4 will be the creation of a final report that states the guidelines for the success of the project, conclusions and findings will be compiled in this report, and then well support a larger service over other regions, rivers sides, and watercourses. The potential of the methodology applied during the WO will be described, but also its limitations. Then, UNDP and other stakeholders will be perfectly aware of the working flow and it's potential.

It is also considered to work with UNDP and GeoSrbija on dissemination activities, and support for determining the viability of using EO for mapping the sources of floating waste. But, also on the integration of the Work Order's product into GeoSrbjia's GIS platform, and assist with data verification and possible future scaling.

To achieve the objectives, following tasks are identified, and will be agreed with ESA and UNDP:

- Task 4.1 - Independent Quality and Verification Check of the output products

- Task 4.2 - Final Report, which includes conclusions and guidelines to an extended project over a larger area.
- Tasks 4.3 - Collaboration with UNDP, GeoSrbjia and stakeholders to ensure the dissemination of the project and integration of EO-Clinic data into their platform.

2.3.5.2 Outputs.

The outputs of this working package will be compiled into the Work Order Final Report. It will include the verification and quality assurance metrics, but also the conclusions and findings of the performed services. It also will include guidelines and limitations of the services, and results from innovative experiments defined in WP3, environmental harm analysis to watercourses.

3 RESULTS AND CONCLUSIONS

3.1.1 WP0 – Management Conclusions

The project was managed following the initially planned schedule although input data was available later in the project (months later after different emails and data interchanges with stakeholders), delaying the project months from its initial schedule.

A final acceptance review and close out meeting is held in September being the end of the project after the initial KOM in March 2020.

3.1.2 WP1 – Data acquisition final decisions and results

The input data that was retrieved or acquired for the project are listed in the table below:

Data	Source	Reception date
List of illegal landfills (2020)	Department of Environment Protection	2020-04-03
List of landfills (circa 2012)	Serbian Environmental Protection Agency (SEPA)	2020-04-03
VHR satellite imagery covering the Lim River AOI (2019)	Pleiades – Airbus	2020-04-06
DEM (SRTM - 30 m)	USGS	2020-04-21
Orthophotos for the Lim river AOI (2009 and 2012, 40 cm)	RGA	2020-06-08
Orthophotos for areas outside of Lim river AOI (2007 and 2012, 40 cm)	RGA	2020-07-09

Table 2. Input data for the project

3.1.2.1 Description of the Area of Interest (AoI)

The area of interest (AOI) consists of a 500 m buffer from the shores of the Lim River within the boundaries of the Republic of Serbia (Figure 4). It covers an area of 92,5 km², situated in western Serbia, a hilly region that includes a mosaic of agricultural and forested landscapes. The main urban areas in the AOI are the municipalities of Priboj and Prijepolje.

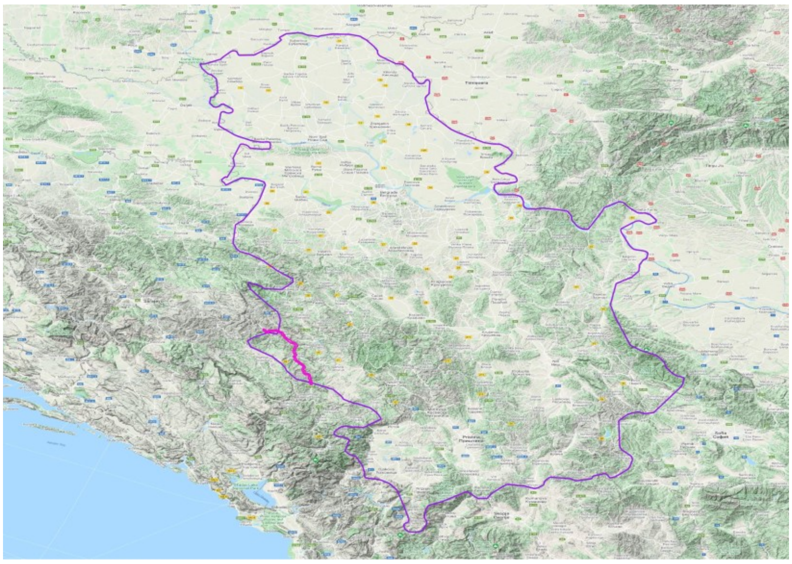


Figure 4 Lim River Area of interest (in pink)

3.1.2.2 Existing waste disposal site inventories

DEP provided us with a list (with location) of known illegal waste disposal sites in the Lim river AOI. This list (DEP2 inventory) contains 22 sites of various sizes.

We retrieved a KMZ file locating 3528 waste disposal sites across Serbia from the SEPA website (http://www.sepa.gov.rs/index.php?menu=207&id=1007&akcija=showExternal&Lang=Latinica). Although no specific date is indicated for the inventory of the sites, we believed that it corresponds to the one referred to by Stanisavljenic et al. [13] in their 2012 study on methane emissions from landfills in Serbia. We therefore assigned a date of circa 2012 to this inventory (SEPA 2012 inventory).

3.1.2.3 Procured High Resolution Imagery and Orthomosaic

Three Pleiades satellite images acquired over the AOI between 2018 and 2019 (2018-11-06: 12.0 km², 2019-07-04: 22.5 km², and 2019-08-06: 58.0 km²) were purchased. Each image consists of four multispectral bands (blue, green, red, near infrared) with a 2-m resolution and a panchromatic band with a 0.5 m resolution. The purchased images were already atmospherically and radiometrically corrected.

The satellite images were orthorectified using the 30 m SRTM DEM, pansharpened at 0.5 cm, colour balanced and then assembled into a single image mosaic. The image mosaic contains four multispectral bands (blue, green, red, near infrared) and has a final resolution of 0.5 m. For most of the AOI, the horizontal spatial precision of the mosaic is estimated at 1-2 m which is deemed acceptable for the mapping of waste disposal sites. However, it is estimated at 5-10 m in the southern portion of the AOI due to the more pronounced topography in that area. This portion of the AOI is sparsely populated, and waste disposal sites are expected to be infrequent.

3.1.2.4 Collected data from Republic Geodetic Authority (RGA) and GeoSerbija

As previously mentioned, the development of a classification algorithm for the detection of waste disposal sites requires a large number of training sites. An insufficient number of training sites could be obtained from the Lim River AOI alone. It was therefore necessary to collect some training sites from areas outside the Lim river AOI.

We used the 2012 SEPA inventory (mentioned above) to analyse the distribution of waste disposal sites across Serbia and identify areas with the highest density of sites. Five areas were identified with high potential for the collection of training sites (Figure 2): Smederovo, Negotin, Krusevac, Nis/Leskovac, Vranje. The outline of these areas was submitted to the RGA which then made available to us 1267 orthophotos (RGB, 40 cm) acquired between 2007 and 2011 and 1475 orthophotos (RGB, 40 cm) acquired between 2011 and 2013. These orthophotos were resampled at 0.5 m in order to have the same resolution as that of the Pleiades images. With the aid of the 2012 SEPA inventory, 497 waste disposal sites were located on the resampled orthophotos. They were used for the extraction of training sites for the detection of waste disposal sites.

RGA also provided us with orthophotos (RGB, 40 cm) acquired over the Lim River AOI between 2009 and 2012. These orthophotos were used to identify zones of erosion along the Lim River between 2009 and 2019 (task 3.3).

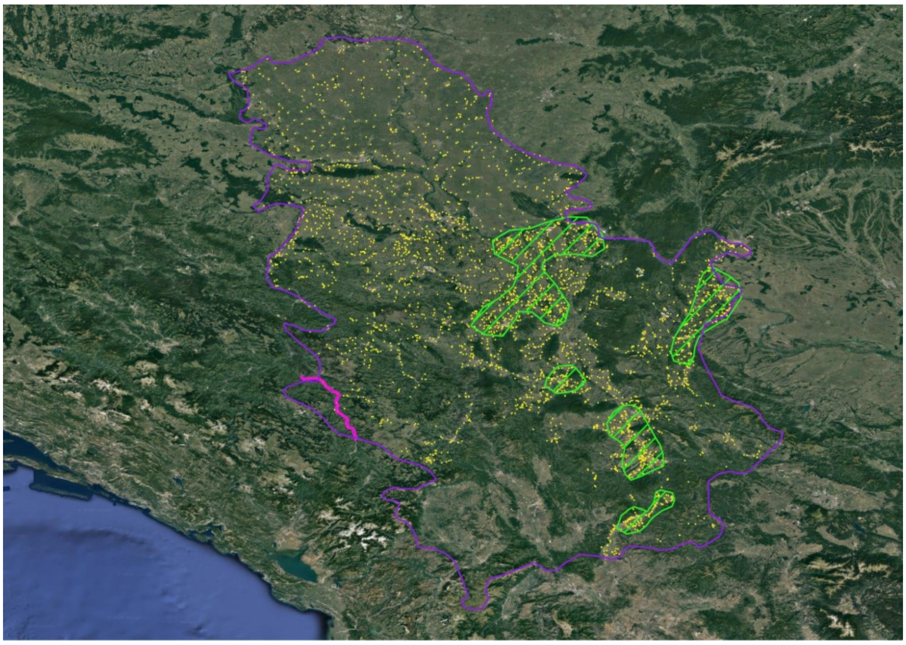


Figure 5 Secondary areas for selection of training sites (primary AOI in pink, secondary areas in green and 2012 SEPA inventory as yellow dots)

3.1.3 WP2 – Service 1 conclusions: Mapping of waste disposal sites along the Lim River

3.1.3.1 Typology of identified Waste Sites

The visual examination of waste disposal sites from the DEP2 and SEPA 2012 inventories on the Pleaides 2019 (for DEP2) and the 2007-2013 orthophotos (for SEPA 2012) led us to characterize four types of waste disposal sites (Figure 3):

- exposed waste
- buried waste
- levelled waste
- industrial waste

The characterization of these types of disposal sites is provided in the Interpretation Guide found in Appendix D. The size of the waste disposal sites observed in the DEP2 and SEPA inventories was very variable, ranging from a few hundred square meter (mostly exposed waste sites) to a few thousand square meters (mostly levelled waste sites). Most exposed and buried waste sites seemed to be illegal (unfenced and without any managing facilities) while most levelled sites are probably legal sites (managed by municipalities). It was often difficult to establish if industrial waste sites were legal or illegal sites.

Exposed waste | Buried waste

Levelled waste | Industrial waste

Figure 6 Four types waste disposal sites used in the mapping

3.1.3.2 Map of waste disposal sites

Three versions of the map of the waste disposal sites detected from the Pleiades 2019 imagery for the Lim River AOI were generated: two maps resulting from the AI classification (one with four classes, one with a single class) and a map resulting from the manual visual interpretation of the imagery. These three maps are provided as outputs from the present work package (WP2).

Map Layer id	File Name	Description	Format
[ML.01]	Effigis_Lim_river_2019_waste_disposal_sites_automated_detection_4classes.shp	Map layer containing waste disposal sites automatically detected (AI classification – 4 classes) on 2019 image mosaic	.shp
[ML.02]	Effigis_Lim_river_2019_waste_disposal_sites_automated_detection_1class.shp	Map layer containing waste disposal sites automatically detected (AI classification – 1 class) on 2019 image mosaic	.shp
[ML.03]	Effigis_Lim_river_2019_waste_disposal_sites_visual_interpretation.shp	Map layer containing waste disposal sites visually interpreted on 2019 Pleiades image mosaic	.shp

Table 3. Map of waste disposal sites (ML – Map Layers)

All three maps consist of a shapefile containing polygons providing the outline of the detected waste disposal sites. The attribute table associated with the shapefile contains the following fields:

- Id: Unique ID for each site
- Class: Type of waste disposal site
- Lat: Latitudinal coordinate of the centroid of the polygon (in decimal degrees)
- Lon: Longitudinal coordinate of the centroid of the polygon (in decimal degrees)
- Area_m2: Area of polygon (in square meters)

All three shapefiles are in the WGS 1984 UTM 34 N projection.

ML.01 contains 1492 waste disposal sites: 1457 exposed waste, 19 buried waste, 5 levelled waste, and 11 industrial. The size of the sites ranges from 3 m² to 1691 m², with about 61 % of the sites being smaller than 100 m².

ML.02 contains 1443 waste disposal sites whose size ranges from 3 m² to 1112 m². Nearly 52 % of them are smaller than 100 m².

ML.03 contains 61 waste disposal sites: 34 exposed waste, 19 buried waste, and 8 industrial. No levelled waste site was observed during the visual interpretation of the 2019 Pleiades imagery. The size of the sites ranges from 25 m² to 14 312 m², with about 10 % of the sites being smaller than 100 m².

3.1.3.3 Waste Sites Report and Statistics

No ground truthing data was available for the validation of the maps produced by automated detection (ML.01 and ML.02). Consequently, we used ML.03 as the reference data for the assessment of the accuracy of ML.01 and ML.02.

The segmentation of the 2019 Pleiades orthomosaic resulted in the creation of 273,738 objects. Out of these, 29,922 were pre-classified as open non-vegetated area. It is these objects that were submitted to the trained AI classifiers.

ML.01 was produced with a first classifier using five possible classes (exposed waste, buried waste, levelled waste, industrial waste, and non-waste). The confusion matrix observed for the 29,022 objects classified with this classifier is provided in table below: This confusion matrix considers the individual objects (29 922) submitted the classifier. Of these, 1669 were classified as exposed. These correspond to the 1457 exposed waste sites contained in ML.01 (after contiguous objects belonging to the same class have been merged together). Similarly, the 69 objects considered as reference exposed sites in the confusion matrix correspond to the 34 exposed waste sites of ML.03 (some of which are associated to several contiguous smaller objects.

		Reference					Total	User Accuracy	Commission error
		Exposed	Buried	Lev-elled*	Industrial	Non-waste			
Classifier	Exposed	10			15	1,644	1,669	0.006	0.994
	Buried	1			1	19	21	0.000	1.000
	Levelled				1	11	12	0.083	0.917
	Industrial	1				4	5	0.000	1.000
	Non-waste	57	48		18	28,092	28,215	0.996	0.004
Total		69	48		35	29,770	29,922		
Producer accuracy		0.145	0.000		0.029	0.944		Overall accuracy	0.939
Omission error		0.855	1.000		0.971	0.056			

* Although the levelled class was not observed in the Lim AOI, it was observed in the areas used for the collection of training sites. As this classifier was developed for possible use in any area of Serbia (not just the Lim River AOI), it is included in the Lim River trial. This would allow to see if levelled sites could be confused with other types of features present in the landscape (which is the case in the Lim River AOI, as shown by the commission errors).

Table 4. Matrix of 29,022 classified objects observed

It can be seen that this classifier does not have a high detection success rate for the different types of waste disposal sites (omission error of 85,5% to 100%) and also creates a very large number of false detections (91,7% to 100%). Consequently, it seems that the accuracy of ML.01 is very low (for the waste disposal sites). This is not too surprising given the low number of training sites available for the buried waste, levelled waste, and industrial waste site types.

The second map (ML.02) was produced with only two classes (Exposed waste site[1], Non-waste site), hoping the AI classifier would yield better results. In this case, we tried to optimise the following classifier parameters: size of analysis window (W) and maximum number of samples (training sites) per class (spc). For ML.01 we had used a window width of 40 pixels (20 m) and a spc of 5000. For map ML.02 we tried different combinations of 2 window widths (W40 - smaller, W80 - larger) and 2 spc sizes (spc5000 and spc10000). The following table gives the accuracy assessment results obtained for the different combinations of parameters:

[1] Including the other types of waste disposal sites (buried, level, industrial) into the same class as the exposed waste sites would have 'polluted' the training data and would have produced unnecessary errors. This second classifier was developed to detect the most common/frequent type of waste disposal site (i.e. exposed), in order to optimize the detection of this type of site only. To include all waste disposal site types into a single class, training data with a more balanced representation of each site type (i.e. a lot more examples of buried, levelled and industrial sites) shall be used.

Classifier (parameters)	Number of objects classified as Non-waste	Number of objects classified as Exposed	Omission error	Commission error	Overall accuracy
1 class-W40_spc5000	27,821	2,101	0.855	0.995	0.928
1 class-W40_spc10000	28,617	1,305	0.899	0.995	0.955
1 class-W80_spc5000	27,399	2,523	0.797	0.994	0.914
1 class-W80_spc10000	28,262	1,660	0.841	0.993	0.943

Table 5. Accuracy assessment results obtained for the different combinations of parameters

It can be seen that the larger number of training sites (spc10000) tends to reduce the number of commission errors, but at the expense of an increase in omission errors. The use of a larger analysis window (W80) allows to slightly diminish the number of omission errors. The classifier using the W80 and spc10000 parameters was therefore selected to produce the ML.02 as it provided some compromise between the decreased commission and the increased omission. However, in comparison to the reference data, the amount of errors (particularly false-detections) associated with ML.02 is still very high and therefore it cannot be considered as very reliable.

3.1.3.4 Potential and limitations of the technique to detect waste sites

The 2012 inventory (kmz file from SEPA) indicated 23 waste sites in the study area, most likely all falling into the ''exposed waste sites" category. The visual interpretation of the 2019 Pléiades imagery revealed 61 sites including 34 exposed waste sites, 19 buried waste sites and eight industrial waste sites, thus showing a sizeable increase between the two years.

Limited success has been obtained for the mapping of waste disposal sites using VHR satellite imagery and a deep learning classifier. Several factors may explain this.

The imagery used for the detection of the waste disposal sites had a pixel resolution of 50 cm. This might not be sufficient to allow for the recognition of this type of feature. For example, during the visual inspection of the DEP2 inventory on the 2019 Pleaides for the elaboration of the Interpretation Guide, it was sometimes difficult to identify with certainty the listed waste disposal sites, particularly when the sites were small. Many times, the recognition of the waste disposal sites was done through the combination of spectral characteristics (colours, patterns) and contextual analysis (presence of bare soil, access by road, relatively flat area, near inhabited area, etc.). The use of satellite imagery with a higher spatial resolution (e.g. 30 cm Worldview-3) or aerial imagery should provide better results.

Access during the project to 20-cm aerial photographs acquired by the Serbian Government over the AOI and surroundings leads us to believe that this resolution would be more suitable for automatic extraction of waste sites. The increased resolution from 50 cm to 20 cm brings more ground details, translating into different image textures, which facilitate the distinction between waste sites and bare ground, parking lots and other non-vegetated features. It would also lead to the improved detection of small waste sites, which can in turn increase the number of potential training sites and feed the AI algorithm.

This being said, commercial satellite imagery, now available at 30-cm resolution with Maxar's WorldView-3 (launched in 2014) and WorldView-4 (launched in 2016) satellites, might also be an interesting alternative. In high demand by, among others, Departments of National Defense around the world, their coverage, however, is not always recent outside urban areas. A quick search in the WV3 and WV4 archives shows that about 60 % of Serbia is covered with 30-cm imagery with less than 20% cloud cover (Lim River area of interest not covered) acquired, for the most part, in 2018. It is of course possible to task these two satellites to acquire new data, but as for getting all input data, it needs to be planed for in advance, and will imply a significant budget increase and possible long delays in acquisition owing to the high demand (**although everis has a DigitalGLobe/Maxar GBBDX license and special prices for images from Maxar as being in partnership for supporting Maxar in Europe**). But just as a reference, and outside the agreement between everis and Maxar, newly acquired 30-cm data costs US$ 32,50 per km² while archive

30-cm costs US$ 22,50 for 4-band products. When compared with 50-cm Pléiades imagery at a cost of US$ 12.50 per km², the increase in cost needs to be carefully taken into account and compared with that of acquiring 20-cm aerial photography.

In either cases, **this increase in resolution also translates into significantly larger data volumes, which in turn leads to more processing time**, more data manipulations and the need for adequate/sufficient processing capabilities.

In general, AI-based classifiers require a very large number of training sites in order to yield adequate performances. As shown in this study, with the 4-class classifier, the classes with a limited number of training sites (buried, levelled, and industrial) generally had lower success rates than the class with a higher number of training sites (exposed). Similarly, the classifiers using a larger number of training sites (spc10000) performed better (less commission) than the classifiers with a smaller number of training sites (spc5000). **The limited availability of a large number of training sites (site location and site imagery) for the different types of waste disposal sites was certainly a limiting factor in the success of this part of the project**.

Between the two types of errors, commission errors were the most numerous. A visual inspection of 100 randomly selected objects classified as a waste disposal site in ML.02 revealed that the most frequent commission errors observed were objects associated with roads (27), buildings (16), the presence of cars (10), and bare soil (7). Several of these features are often associated with the presence of a waste disposal site (roads, bare soil). Therefore, the nature of the features to be detected (i.e. waste disposal sites) might also explain the difficulty to attain adequate detection rates. More specifically, because bare soil and roads were almost always present (associated) with waste disposal sites, the classifier might have trained itself to recognise roads and bare soil rather than waste heaps. The great variability in size of the waste disposal sites also made their recognition more difficult. Finally, waste disposal sites are a relatively rare feature in the landscape under study: only a total of 61 sites, usually small, over an area of nearly 100 km² (152 objects among 29,922). The rarity of the feature to be detected requires the development of classifiers with very small margins of error.

Therefore, as a summary, given the need for producing a representative map showing the distribution of waste disposal sites for a country such as Serbia in an automated and cost-effective manner, a certain number of factors would help improve the results obtained in this first, exploratory study:

- The resolution of input imagery should be increased from 50 cm to 20 cm if and when recent aerial photography is available and if not, at least to 30 cm by acquiring WorldView-3 and -4 imagery.
- More time should be allowed to test with other AI algorithms/approaches and tweak their parameters (window size, etc.)
- Additional methodological steps should be incorporated such as thresholding to take into account, for instance, the distance between waste sites and roads. In other words, pre-processing that would eliminate all non-vegetated objects located far from roads (≥ 30 m from a road) could help reduce the number of false alarms (commission errors). This process would be facilitated by having access to an up-to-date road layer from Government authorities.
- The number of training sites should be increased, when possible, for all types of waste sites. As it appears in this case that buried, levelled and industrial waste sites are relatively uncommon, focus should probably be placed on only one type, that is ''exposed waste sites''.
- The impact of using a different data set for training (40-cm aerial photography resampled to 50 cm) and for the actual classification (50-cm Pléiades) needs to be assessed as this may affect to some extent the results of the classification. Ideally, the same data should be used for both the training and the information extraction/mapping process.

3.1.4 WP3 – Service 2 conclusions: Environmental Harm Analysis

3.1.4.1 Solid Waste Detection

3.1.4.1.1 Map of Solid Waste detection

The shapefiles produced are detailed in the Table 6 below.

Map Layer id	File Name	Description	Format
[ML.01]	ESA_CLINIC_LimRiverExtent_UTM34N	This is a map layer that contains the spatial extent on the investigated area (Pleiades image, 2018-2019)	.shp
[ML.02]	ESA_CLINIC_LimRiverMaskedSectors_UTM34N	This is a map layer that contains the sectors masked out due to the presence of glint, turbulence or cliff shadows (Pleiades image, 2018-2019)	.shp
[ML.03]	ESA_CLINIC_LimRiverExploitableSectors_UTM34N	This is a map layer that contains the sectors where wastes were looked for (Pleiades image, 2018-2019)	.shp
[SW.01]	ESA_CLINIC_WasteDetection_Pleiades_20182019_points_UTM34N	This is a map layer that contains detected individual solid wastes from Pleiades image (2018-2019)	.shp
[SW.02]	ESA_CLINIC_WasteDetection_Pleiades_20182019_polygones_UTM34N	This is a map layer that contains detected areas where solid wastes may be present from Pleiades image (2018-2019)	.shp
[BU.01]	ESA_CLINIC_buffer_200m_UTM34N	This is a map layer that contains 200m buffers around dumping areas	.shp
[BU.02]	ESA_CLINIC_buffer_500m_UTM34N	This is a map layer that contains 500m buffers around dumping areas	.shp

Table 6. List of shapefiles related to waste detection

Total length of the Lim river is 87 km. Total area of investigation is of 7,6 km² 5 [ML.01]. The total area exploitable to detect the wastes is of 6,4 km² [ML.03]. The map the exploitable and masked areas is synthetized in Figure 7 That also displays the wastes that were detected.

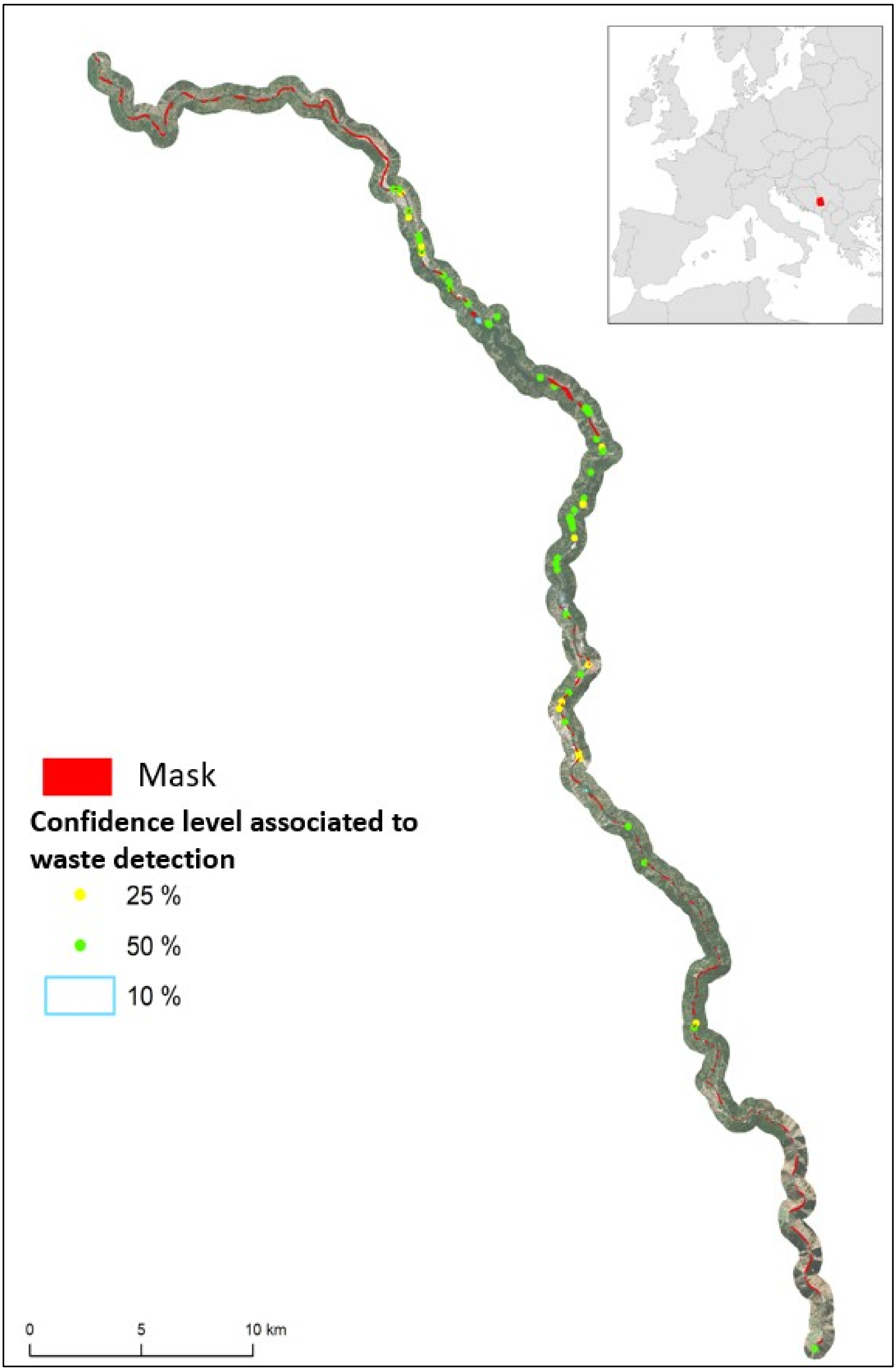


Figure 7 Location of the wastes detected along the Lim River based on Pleiades data acquired in 2018 and 2019

3.1.4.1.2 Typology of identified solid waste

Due to the low resolution of the input image (50 cm) the waste nature could not be identified.

3.1.4.1.3 Solid Waste Report and Statistics

A total of 84 individual floating objects have been identified on the Pleiades images [SW.01] (see above Table 6). The maximum confidence level has been attributed to four-fifth of the data base (Figure 8).

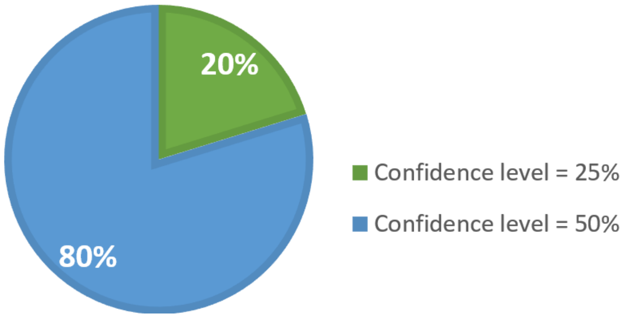


Figure 8 Confidence level of the waste retrieval in the Lim River based on Pleiades imagery

In addition, 5 sectors, where the presence of floating objects is suspected, have been contoured [SW.02].

In order to analyse waste location as a function of waste site location, we used the sites included in UNDP_Serbia_Lim_River_2019_inventory file that highlights 67 landfills, classified as follows:

- Buried waste (14),
- Exposed waste (16),
- Industrial waste (7),
- Uncertain (30).

Among these 67 waste sites, 21 appears unlikely to be potential sources of wastes for the Lim River, when 26 are directly linked to the watercourse and therefore potentially sources of wastes. The remaining 20 may be rubbish sources, but not as obvious as the previous ones.

64% of the floating objects are located less than 200 m from a landfill [BU.01] (Figure 9), which demonstrates a clear relation between the waste location and the probability of the dumping areas to be sources of waste. It is also found that rubbishes are observed in the vicinity of any type of landfills, even and especially buried sites (Figure 10). Industrial dumping areas are rarely correlated with waste observation..

Within a radius of 500 m from the waste sites [BU.02] (see above Table 6), 96 individual rubbishes are observed, some of them being observed several times. Again, the floating objects are more likely related to dumping areas located at a short distance from the river (Figure 11). Buried sites are associated with the largest number of rubbishes when wastes are rarely found in the vicinity of industrial waste sites (Figure 12).

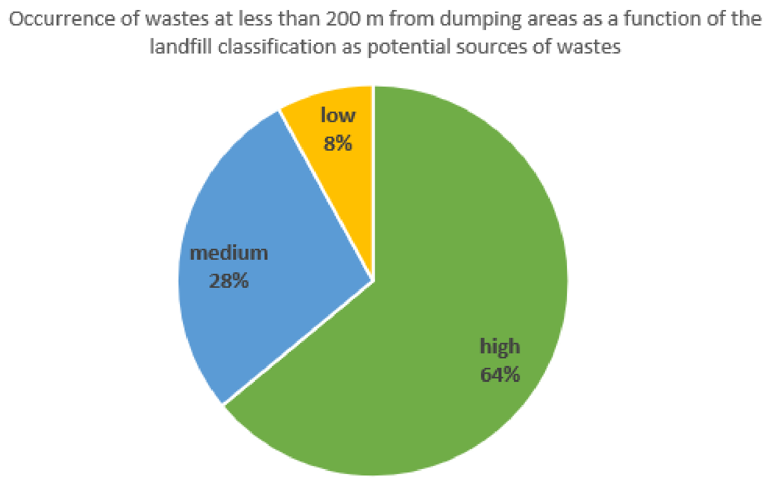


Figure 9 *Occurrence of wastes at less than 200 m from dumping areas as a function of the landfill classification as potential sources of wastes*

Figure 10 *Occurrence of wastes at less than 200 m from dumping areas as a function of the landfill nature*

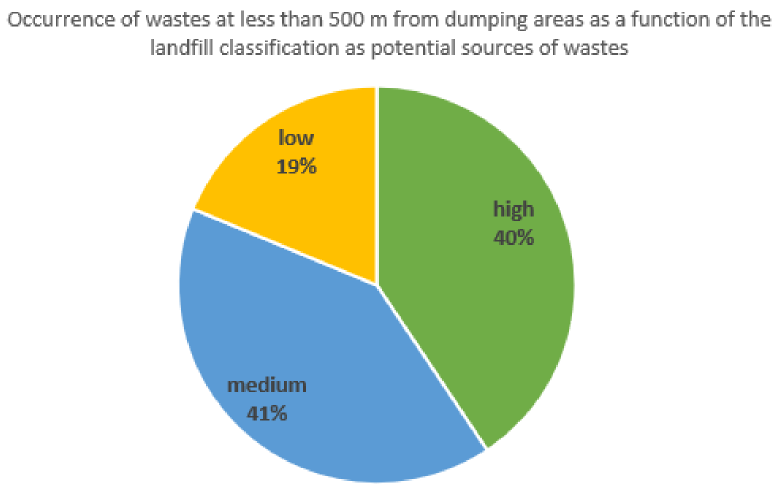


Figure 11 *Occurrence of wastes at less than 200 m from dumping areas as a function of the landfill classification as potential sources of wastes*

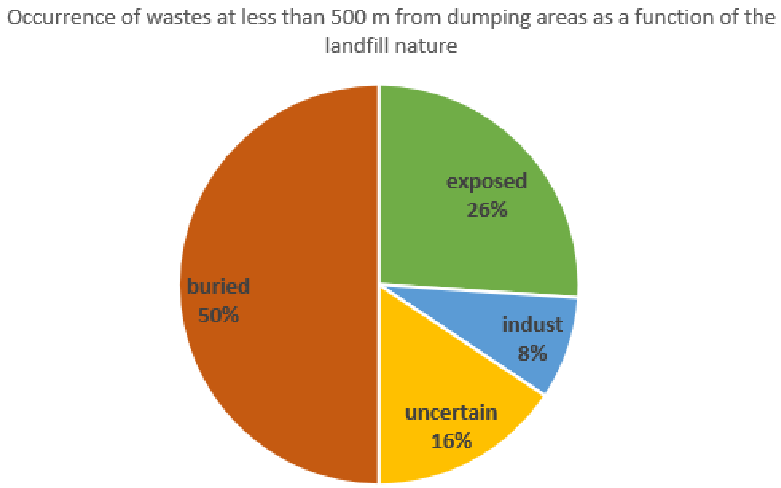


Figure 12 *Occurrence of wastes at less than 500 m from dumping areas as a function of the landfill nature*

3.1.4.2 Organic/Non-Organic particles in the water column

3.1.4.2.1 Proposed strategy to monitor water quality anomalies

In order to detect water quality anomalies within the Lim river, the following strategy is proposed.

First, a database of cloudless/snowless Sentinel-2 images (level L2A) available on the area is constituted. In each image, every water pixel is converted to SPM concentration using a semi-analytical generic algorithm (Nechad *et al.*, 2010 [10]).

Second, a transect line shapefile is drawn all along the Lim river passing approximately in the middle of the river. This transect is further cut into a series of smaller transects of approximately 500m long. Any manmade (bridges, dams, etc.) or natural (banks, etc.) structures are excluded from the transects to focus only on pure water pixels.

Third, for each Sentinel-2 image of the database, the SPM values of pixels intersected by each transect is retrieved and averaged. This operation creates a temporal database of average SPM concentrations for each transect along the Lim river. This database is further statistically analysed to detect temporal anomalies, i.e. any SPM values that is higher than a threshold defined as:

$$SPM_t > tMEAN_{SPM} + 2.5 * tSTD_{SPM}$$

where SPM_t is the SPM value at time *t*, $tMEAN_{SPM}$ is the temporal mean of SPM value for the transect and $tSTD_{SPM}$ is the temporal standard deviation of SPM value for the transect.

Results of this analysis are further exported as an anomaly shapefile for each date for which a Sentinel-2 data is available. Each detected anomaly is then compared with the Sentinel-2 image to interpret whether the anomaly is due to natural causes or can be considered as suspicious if it is localized and close to a detected waste site.

3.1.4.2.2 Water quality anomalies results

The Sentinel-2 database is composed of 105 images collected between 2018 and 2019. The number of images used per month is presented in Figure 13. The temporal distribution of the collected images is clearly seasonal with significantly more images during summer time than during winter time. Besides, luckily, the area of interest is located on the overlapping area of two consecutive orbits which increases the satellite revisit to 2.5 days instead of 5 days. This explains why we have as much as 10 images available in certain months.

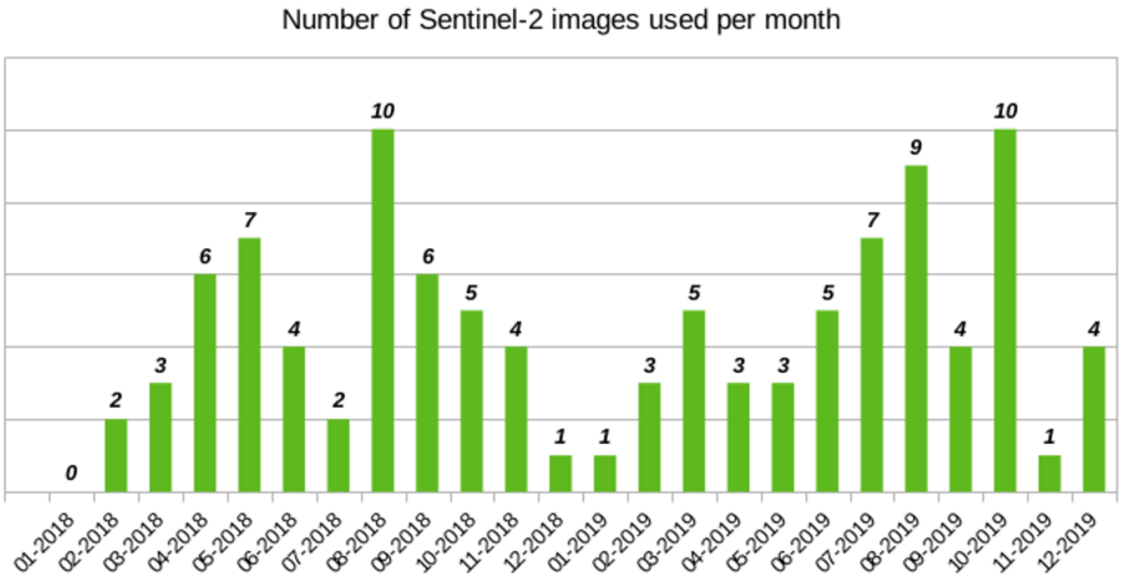


Figure 13 Sentinel-2 images used per month between January 2018 and December 2019

The area of interest is completely covered by two adjacent Sentinel-2 tiles (T34TCN and T34TCP), but because of the sensor spatial resolution (10m), the narrow upstream part of the river could not be analysed through our approach. The complete analysed segment of the river is displayed in Figure 14. A total of 120 transects were considered in the analysis, mainly located in the downstream part of the river.

A total of 432 anomalies were detected within the 120 transects and the 105 images. Detected anomalies can be categorized in 5 groups:

- cloud and cloud shadows not properly masked (118 anomalies - ~27%). These anomalies are detected throughout the year and all along the river,
- glint effects (26 anomalies - ~6%). These anomalies are detected mostly in May, June and July, close to the summer equinox when the sun has the highest elevation angle. They appear in localized area (one or two adjacent transects) where rapids most probably occur,
- temporary natural global events (224 anomalies - ~52%). When temporary meteorological events occur (probably snow melt or heavy rains), the SPM concentrations rise throughout the river and cause the detection of many anomalies on a single date. They especially appear on 7 different dates in late winter 2018 (06/02/2018, 11/03/2018, 31/03/2018, 12/04/2018, 20/04/2018) and late spring 2019 (09/06/2019, 19/06/2019),
- temporary natural local events (43 anomalies - ~10%). These anomalies were mainly detected on 2 dates and correspond to a significant rise in SPM concentrations in the Potpecko lake on 10/05/2018 and downstream of the Drinsko-Limske hydropower plant on 21/06/2018,
- suspicious local events (21 anomalies - ~5%). These increase in SPM concentrations are very localized (1 to 4 adjacent transects) and do not seem to be related to an upstream change in water colour. Three different events were detected and will be further detailed in the next section.

Illustrated examples of the four first group of anomalies are given in Table 7.

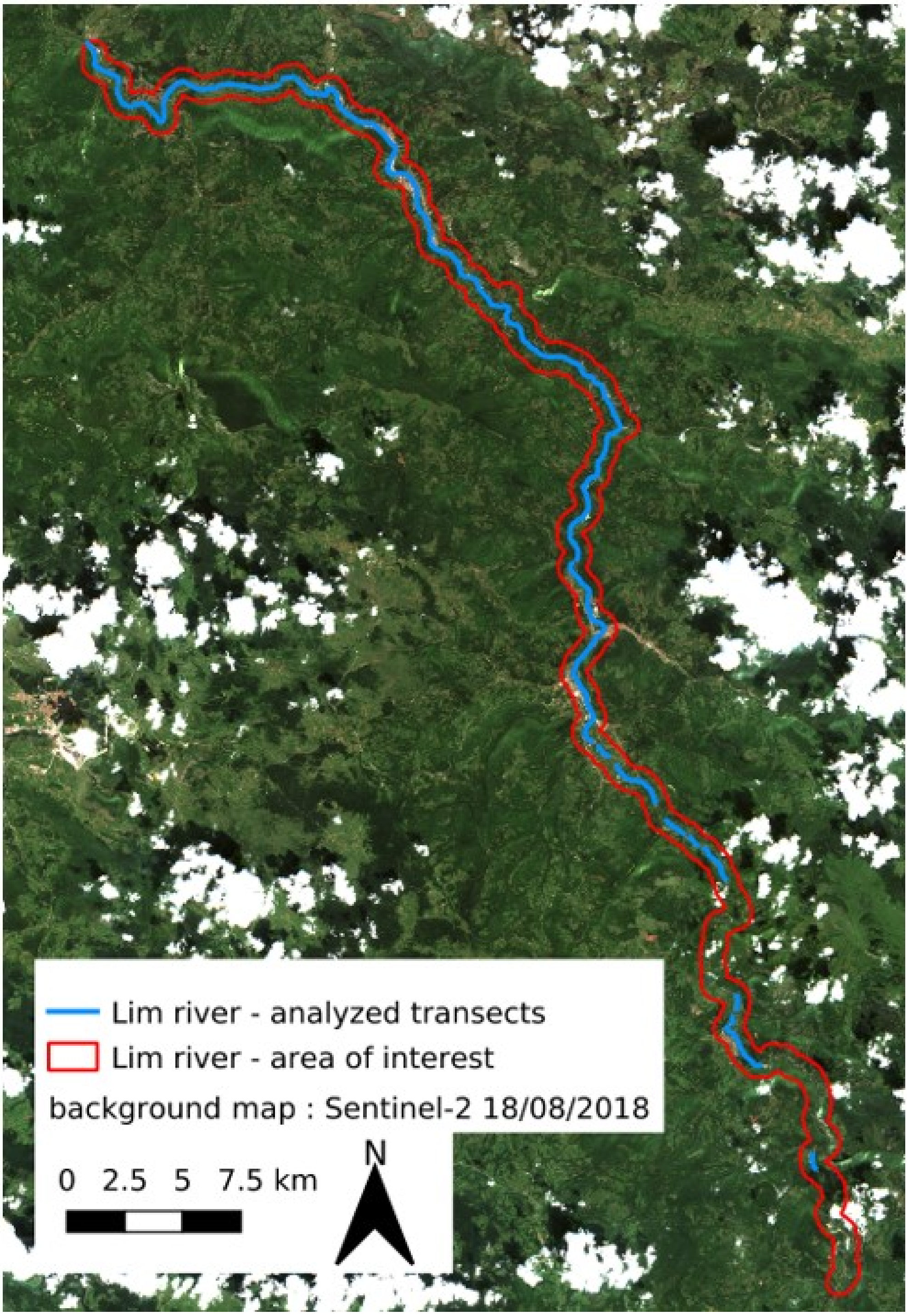


Figure 14 Location of the Area of Interest and analysed transects

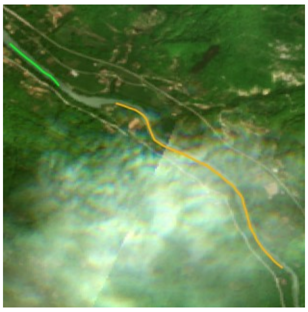
Description	Date	Latitude	Longitude	Image of the area
Cloud effect	30/04/2018	43.302	19.707	
Glint effect	25/05/2019	43.475	19.65	
Global event	19/06/2019	43.562	19.542	
Local event	10/05/2018	43.486	19.639	

Table 7. Examples of non-suspicious anomalies

To push the analysis a little bit further, the frequency of anomalies per transect and the SPM concentration threshold were plotted (Figure 15 below) in order to identify areas where either anomalies are more frequent or SPM levels are frequently higher.

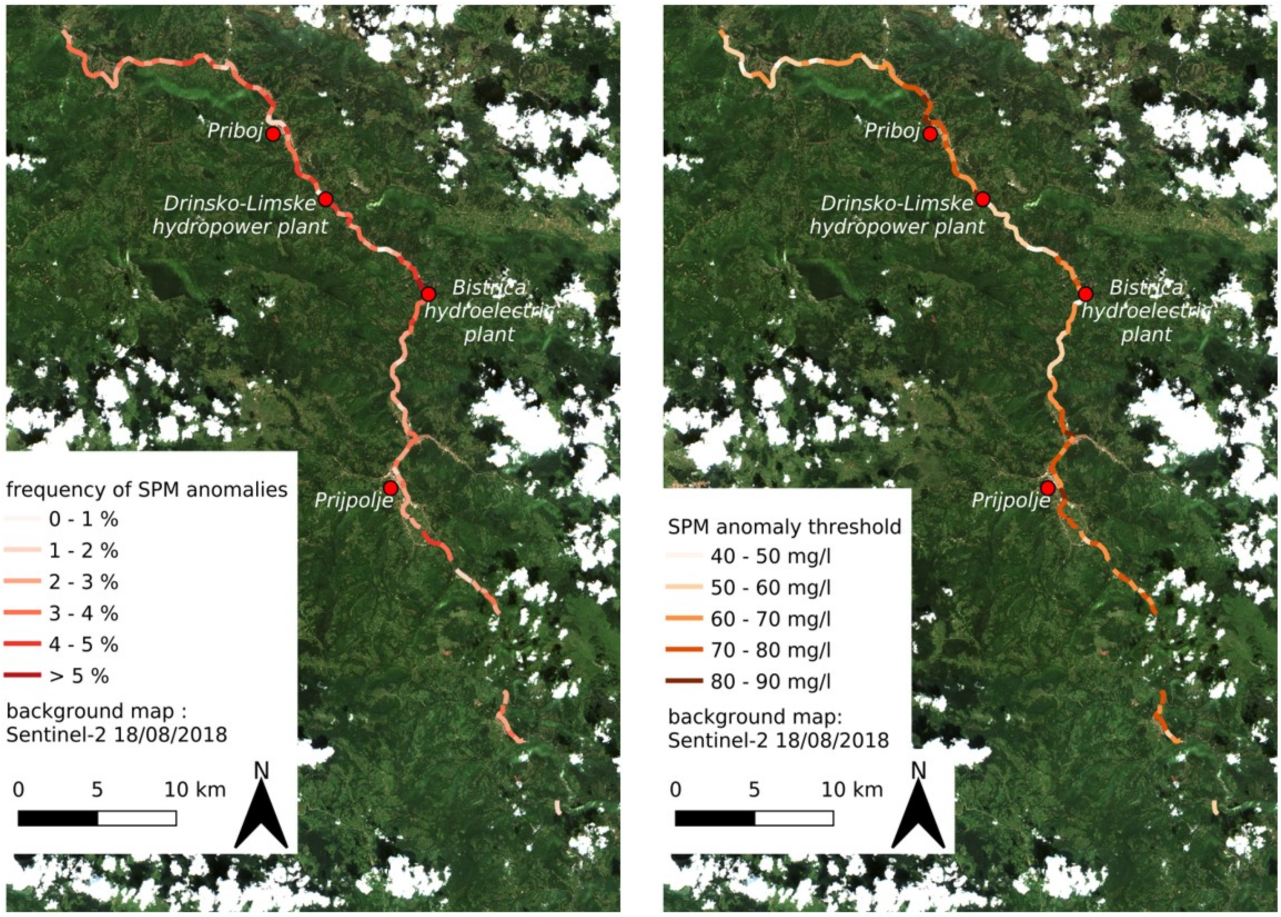


Figure 15 Frequency of anomalies per transect (left) and SPM anomaly threshold (right)

The map of frequency of anomalies (Figure 15- left) shows that anomalies tend to appear more frequently in the downstream part of the river after the hydroelectric plant of Bistrica. A slightly higher frequency is also observed in the upstream part of Prijepolje further South. Yet, since a significant part of the anomalies (~ 52 %) are related to global events that affect the entire river, conclusion on the frequency of anomalies are difficult to draw.

On the other hand, the map of SPM threshold (Figure 15– right) clearly displays difference in the average level of SPM in the river. Higher levels of turbidity are clearly observed in the downstream section of the Drinsko-Limske hydropower plant which tend to extend to the urban area of Priboj. Similarly, the surroundings of Prijepolje are also characterized by higher levels of SPM.

It should be noted here that the values of SPM concentrations displayed in Figure 15 are most probably over-estimated. This is mainly due to the use of land reflectance level 2 products instead of water reflectance products and also to the fact that the river is narrow in most parts and water pixels are probably polluted with reflectance coming from neighbouring land pixels (adjacency effects). Still, as this study relies on relative values, this was not considered as an issue.

3.1.4.2.3 Suspicious anomalies and link to indexed waste sites

In this section, we will have a closer look at three different local suspicious events and try to investigate whether or not these events could be related to a close-by waste site.

The first event occurred on 14/07/2018 in the downstream part of the river close to the Bosnian border (Figure 16). A clear increase of SPM concentrations appears suddenly in the middle of a meander. Two potential waste sites are located close by. Yet, it seems not plausible that this increase in turbidity could be related to those waste sites. The sudden increase seems to propagate further downstream, indicating a significant source of suspended particles. A small tributary (not clearly visible in Sentinel-2 data) flows into the Lim river in this meander and could explain this sudden rise in turbidity.

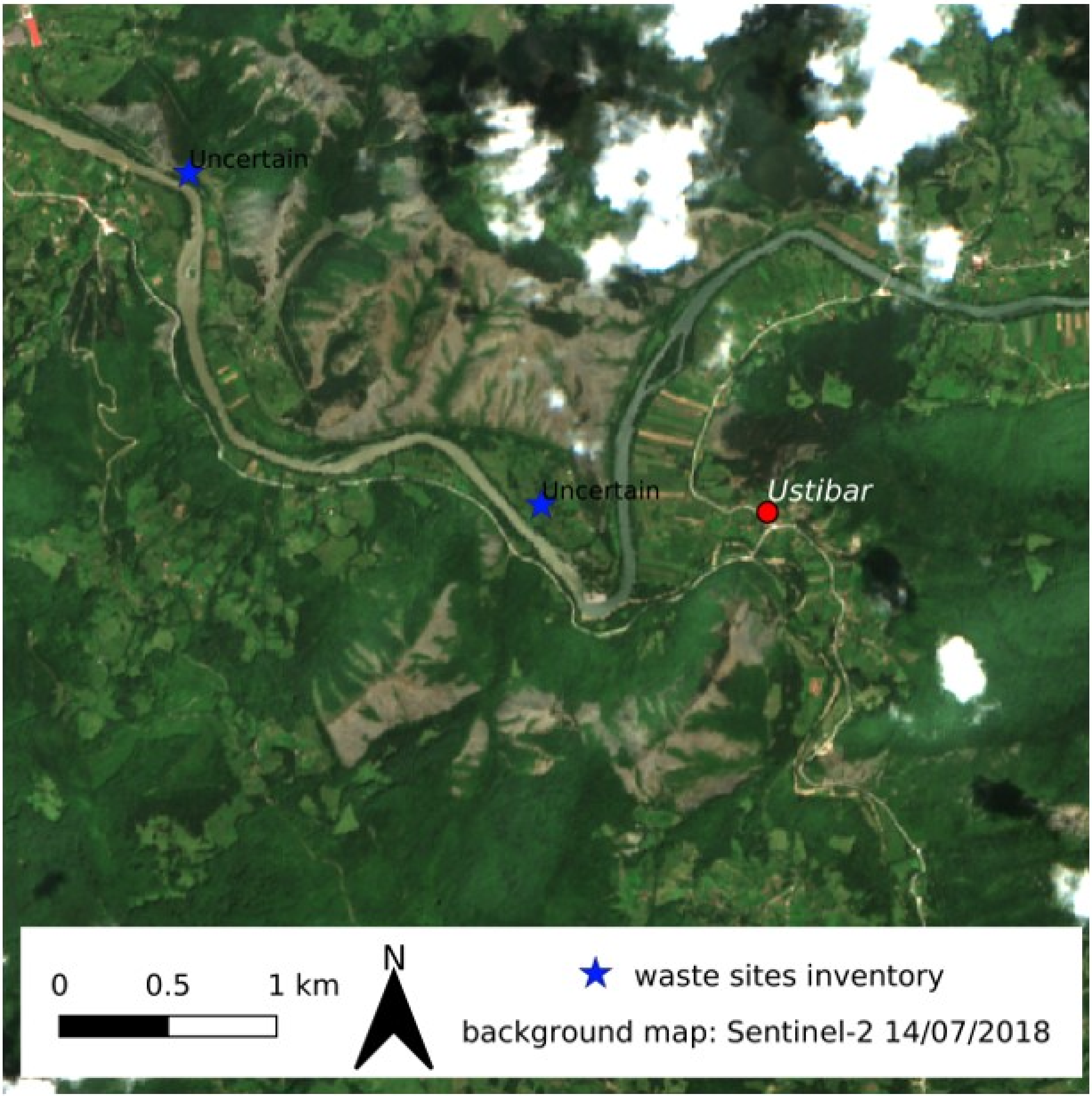


Figure 16 Anomaly detected on 14/07/2018

On 18/08/2018, a local increase in SPM concentration is observed close to the hydroelectrical plant of Bistrica (Figure 17 - left). Even if the increase propagates further downstream, it attenuates quickly around the up-stream part of lake Potpecko. Another Sentinel-2 image was acquired two days later (20/08/2018), but does not display any anomaly in this area. It reappears a few days later (25/08/2018), although with less intensity (Figure 17– right). The presence of two buried waste sites upstream could have something to do with this event but this cannot be confirmed without further investigations. Besides, a moderate increase in turbidity is also observed further upstream around that time, this segment could also be an accumulation zone of suspended particles.

Finally, on the 20/08/2019, a local increase of SPM concentration is observed near the town of Priboj (Figure 18). Many waste sites were identified in the area but none of them seem to be close to the source of particles located more upstream close to what could be a construction site or a warehouse.

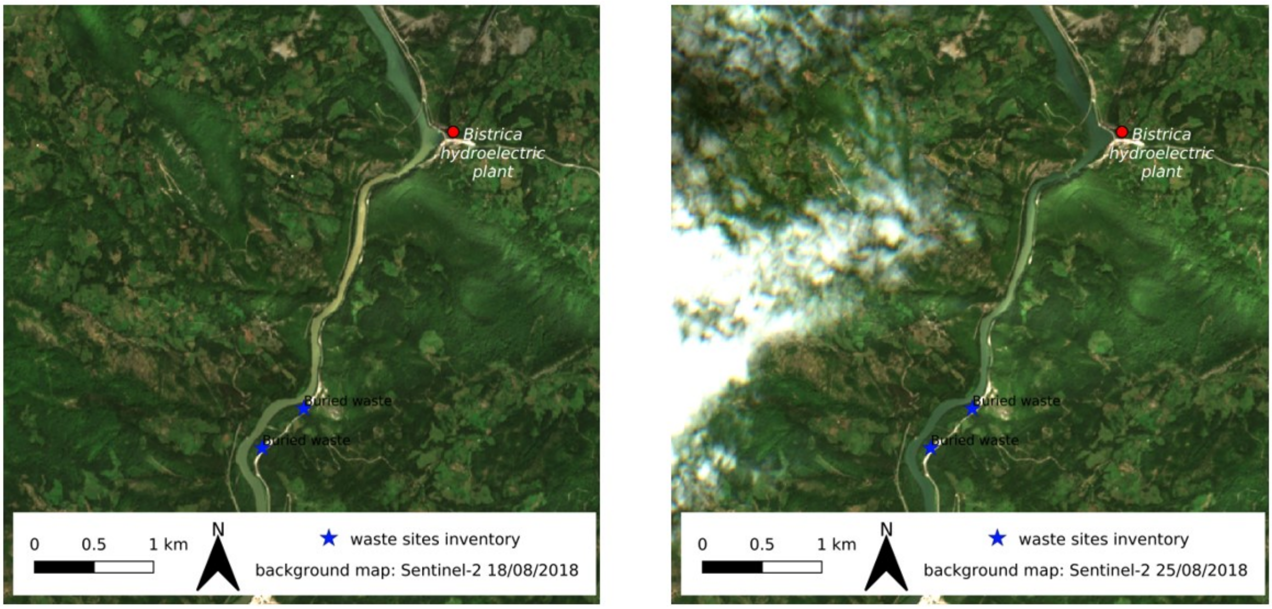


Figure 17 Anomalies detected on 18/08/2018 (left) and 25/08/2018 (right)

Final results are delivered as shapefiles following the description given in Table 8.

Map Layer id	File Name	Description	For-mat
[ML.04]	YYYYMMDD_anomaly_SPM.shp	Series of 105 shapefiles containing SPM anomalies detected along the Lim river for S2 data acquired on YYYYMMDD (YYYY = year, MM = month, DD = day). Anomaly attribute: 0 = no anomalies detected, 1 = probable natural anomaly, 2 = false positive (cloud or cloud shadow), 3 = suspicious anomaly	.shp
[ML.05]	anomaly_SPM_freq.shp	This is a map layer that contains the frequency of anomalies per transect	.shp
[ML.06]	anomaly_SPM_thresh.shp	This is a map layer that displays areas where either anomalies are more frequent or SPM levels are frequently higher than a threshold defined as: $SPM_t > tMEAN_{SPM} + 2.5 * tSTD_{SPM}$	.shp

Table 8. Definition of the shapefiles carried out to demonstrate SPM anomalies along the Lim River

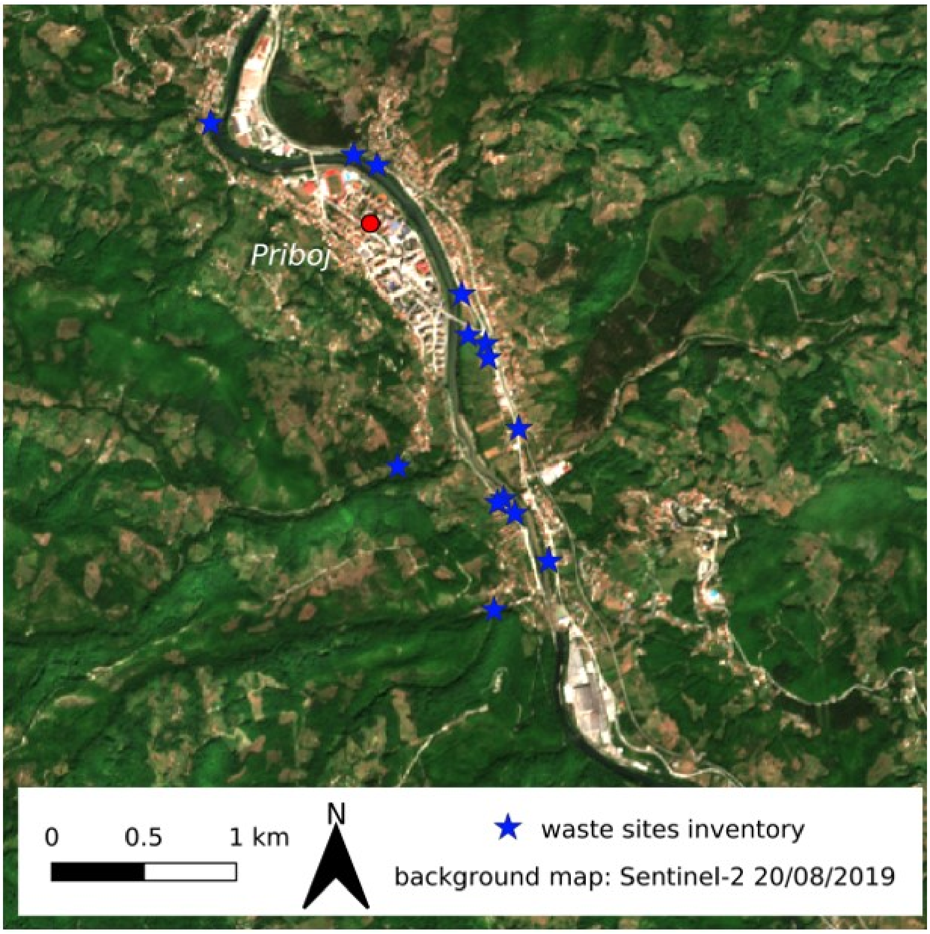


Figure 18 Anomaly detected on 20/08/2019

3.1.4.3 Riverbank erosion

3.1.4.3.1 Map of riverbank erosion locations

The final results delivered to UNDP are detailed in Table 9.

Map Layer id	File Name	Description	Format
[ML.07]	Right_bank_change_2012_2019.shp	This is a map layer that contains right riverbank change along 50-m interval transects from 2012 to 2019	.shp
[ML.08]	Left_bank_change_2012_2019.shp	This is a map layer that contains left riverbank change along 50-m interval transects from 2012 to 2019	.shp
[ML.09]	Right_bank_area_change_2012_2019.shp	This is a map layer that contains right riverbank area change from 2012 to 2019	.shp
[ML.10]	Left_bank_area_change_2012_2019.shp	This is a map layer that contains left riverbank area change from 2012 to 2019	.shp
[ML.11]	bank_change_landfill_500m.shp	This is a map layer that contains riverbank changes from 2012 to 2019 within a 500-m perimeter around each landfill	.shp

Table 9. Details of the shapefiles focusing riverbank erosion location

The riverbank evolution along the Lim river was statistically analyzed between 2012 and 2019 from very high-resolution images, using two different methods:

- Variation of the left and right bank positions along perpendicular profiles spaced 50 m apart ([ML.07], [ML.08] – see above Table 9). This result allows to visualize the annual change rates along the river with a value every 50 m,
- Surface variation of the riverbanks ([ML.09], [ML.10]). This result makes it possible to quantify a balance of gain and lost surfaces and spatialize them.

The left riverbank was analyzed on 1320 profiles. The overall average change rate is -0.39 m/year ± 0.09 m/year, with significant variability between -9.3 m/year and 9.08 m/year. Among the nearly 80-km long analyzed, 59.02% of the left bank have statistically significant erosion, and 18.48% of the profiles are in significant accretion. Therefore, 22.5% of the transects show no change between 2012 and 2019.

The right riverbank was analyzed on 1620 profiles. The number of transects differs from that of the left bank due to the different morphology between them and the presence of shadows on the images preventing the bank detection. The overall average rate is -0.12 m/year ± 0.09 m/year, with significant variability between -8.91 m/year and 11.25 m/year. The results show that 35.56% of the left riverbank have statistically significant erosion, and 34.07% of the profiles are in significant accretion. Therefore, 30.37% of the transects do not show any change between 2012 and 2019.

In some cases, the erosion of one bank faces an accretion of the other, which shows a river migration (Figure 19 to Figure 22). In other cases, the erosion of a bank is not counterbalanced by the accretion of the opposite one. Sometimes even, both banks are eroding in the same sector.

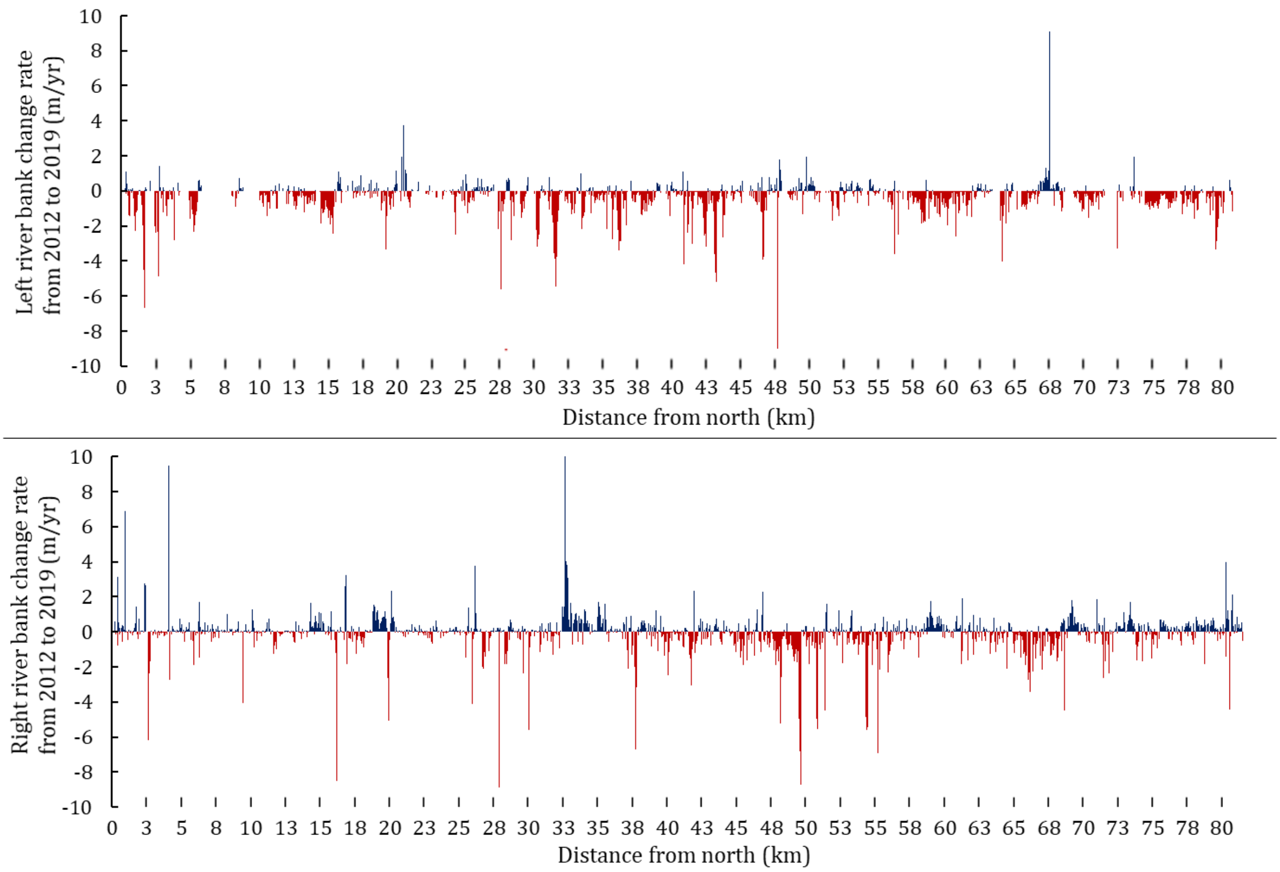


Figure 19 Left (top graph) and right (bottom graph) riverbank change rates along 50-m spaced profiles from 2012 to 2019

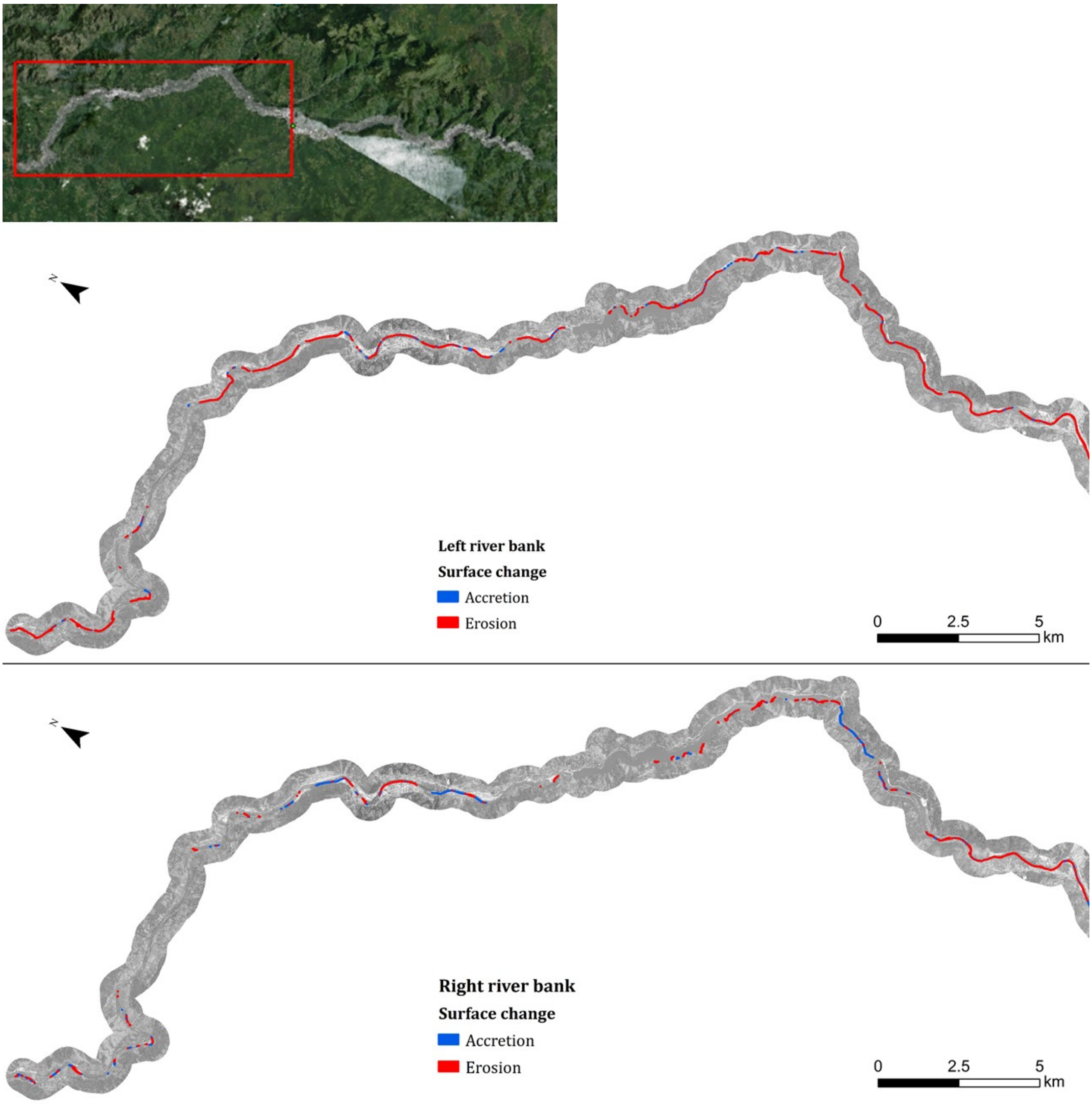
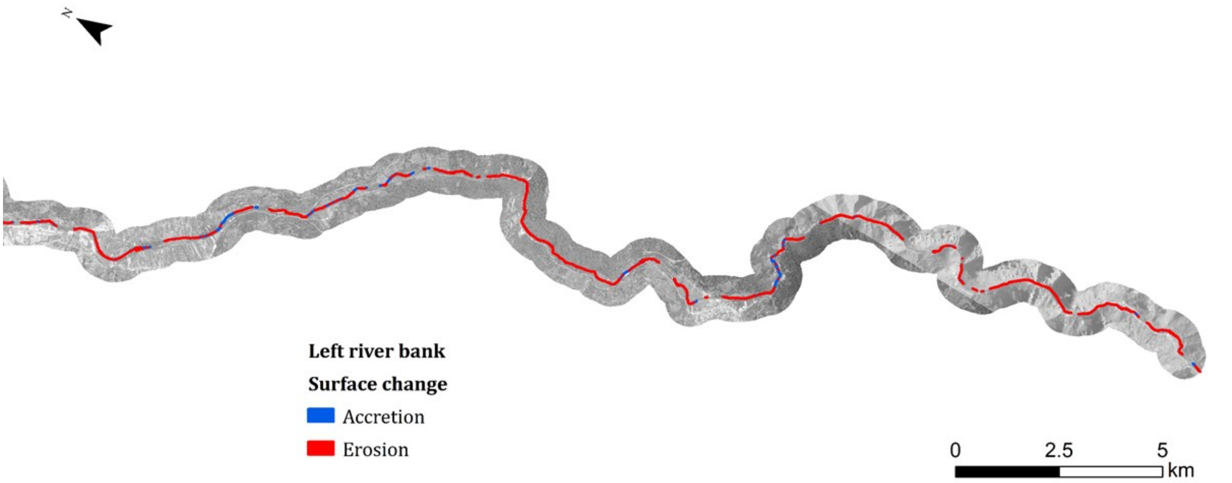


Figure 20 *Left (top graph) and right (bottom graph) riverbank area changes along the first half of the Lim river from North from 2012 to 2019*



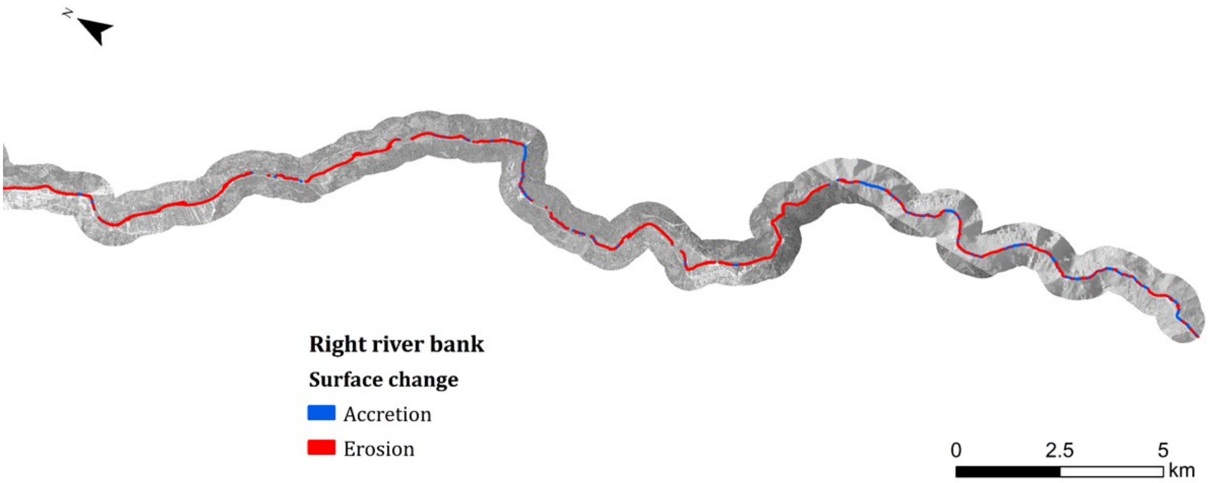
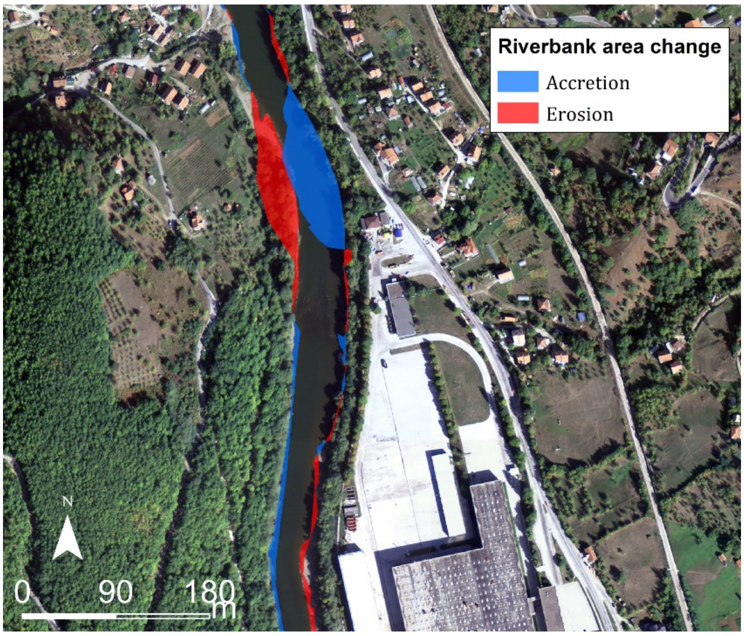


Figure 21 *Left (top graph) and right (bottom graph) riverbank area changes along the second half of the Lim river from North from 2012 to 2019*



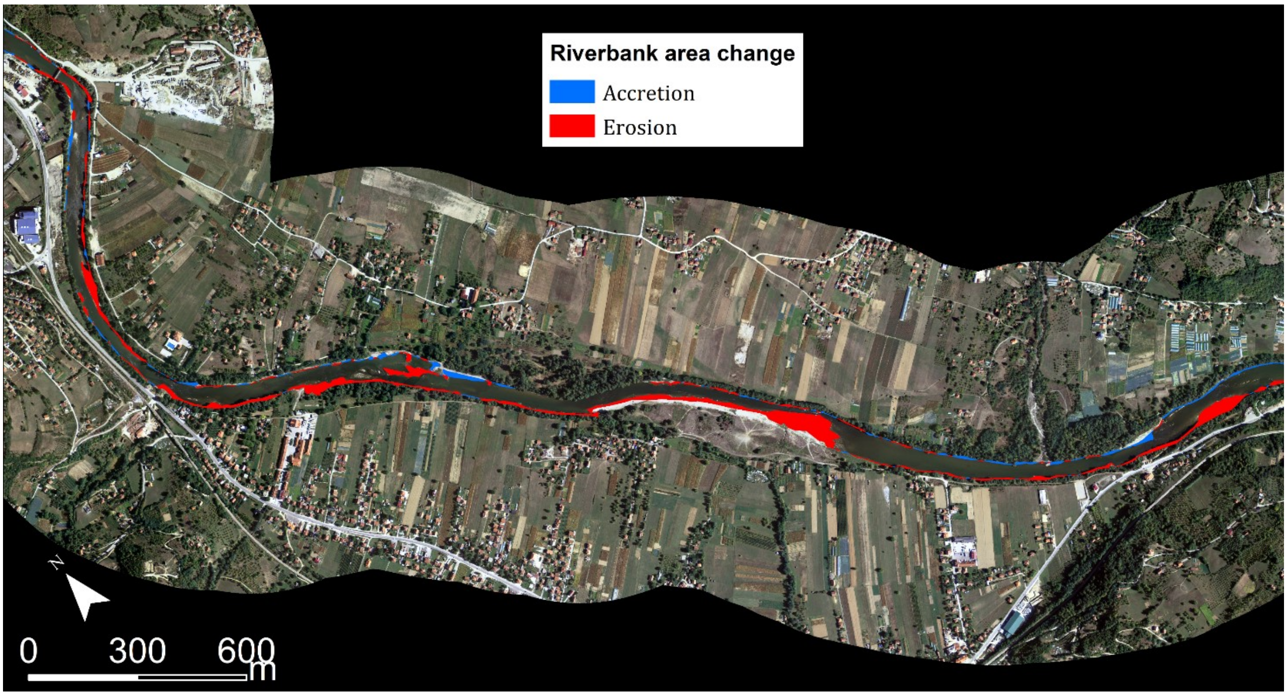


Figure 22 Example of river portion where riverbank erosion dominates

3.1.4.3.2 Major risk of erosion of riverbanks connected to landfills

The variation in the right riverbank position has been extracted over a perimeter of 500 m around each localized landfill ([ML.11], Table 10).

Among the 67 landfills listed along the Lim River, 55 are within a 500m perimeter where bank erosion dominates, representing more than 80% of the landfills (Figure 23). The total of these bank changes shows a total erosion of 118,151 m^2, while the evolution of the whole riverbanks is 235,709 m^2. In these areas, half of the bank surface lost along the river is therefore located near the landfills.

Riverbank erosion is a natural process that contributes to transform streams. This phenomenon increases in areas with concave banks. The erosion is also exacerbated when an obstacle disturbs the current (Degoutte, 2006 [4]). A logjam caused by a waste accumulation after runoff transport can cause the erosion of opposite bank, by reflected current (Figure 24).

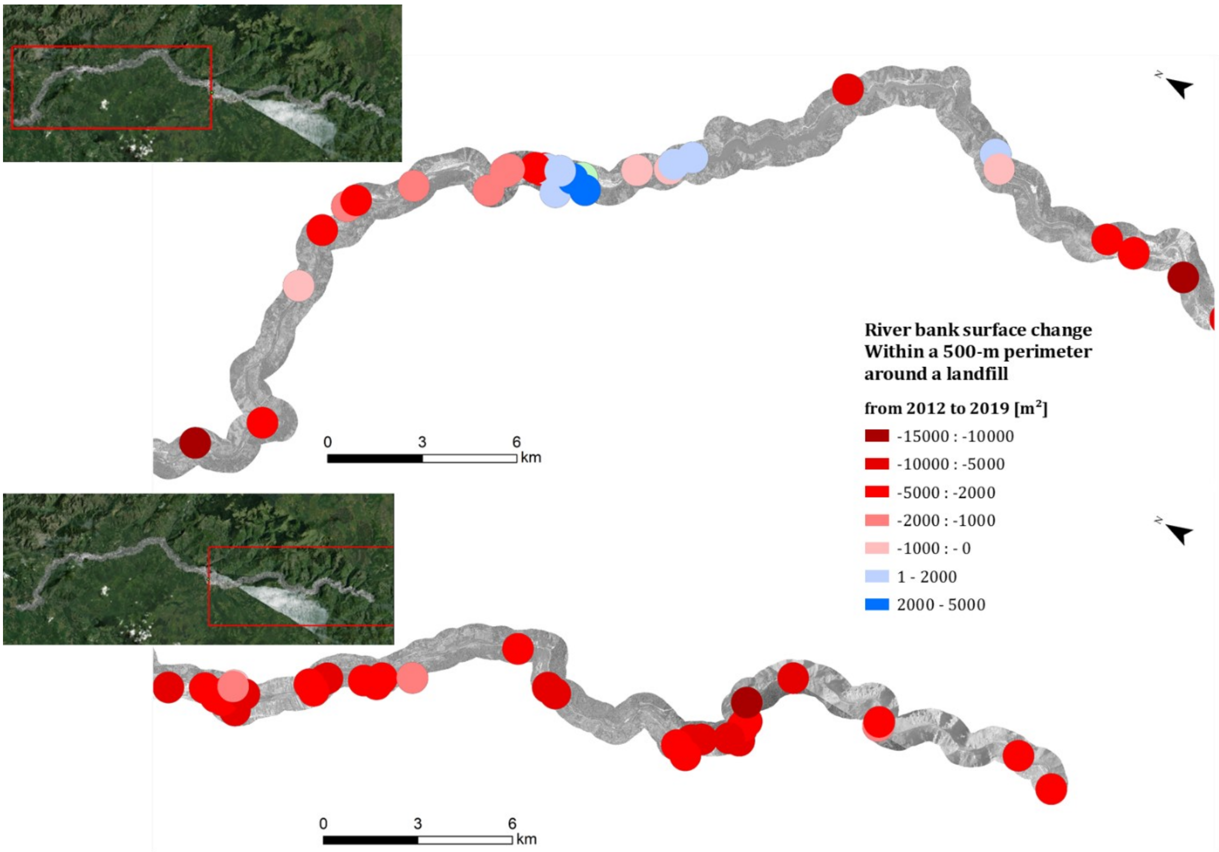


Figure 23 Map showing riverbank changes over a 500-m perimeter around each landfill

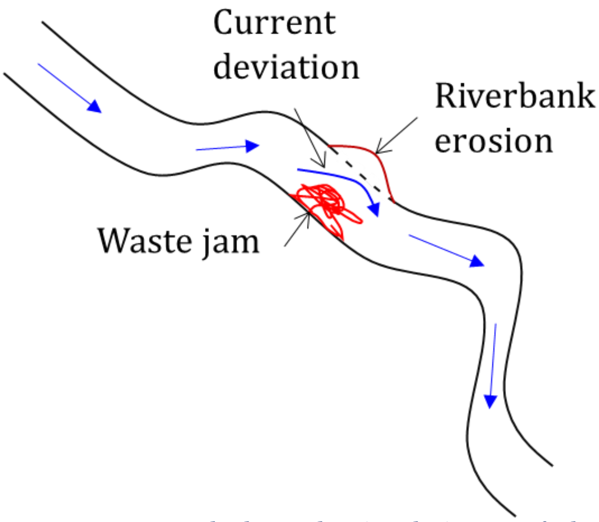


Figure 24 Conceptual scheme showing the impact of a logjam caused by waste jams

Riverbank erosion may cause various types of damage:

- An increased release of suspended particulate matter which can disturb the quality of water (pollution, eutrophication) and the ecosystem balance of the environment,
- Habitat destruction,

- Ground movements and collapses that could endanger nearby settlements.

3.1.4.3.3 Future riverbank position

The example of the projected future position of the right riverbank makes it possible to estimate the location of areas at high risk of erosion for the coming decades if the current trend continues ([ML.12], [ML.13], Table 10). This information can be a useful tool helping to decide on protective measures, but it remains qualitative. On the other hand, it requires a real effort of thematic analysis because some bank retreats can be refuted by the geomorphological characteristic of the environment. For example, in Figure 25, the southern extremity (right side of the image) shows recent strong erosion, which manifests as a significant retreat in the bank's position in the coming decades. However, it was about the disappearance of an emerged pebble bank which marked the limit of the bank. The erosion of an indurated bank is not as rapid as the submersion of a mobile sediment bank.

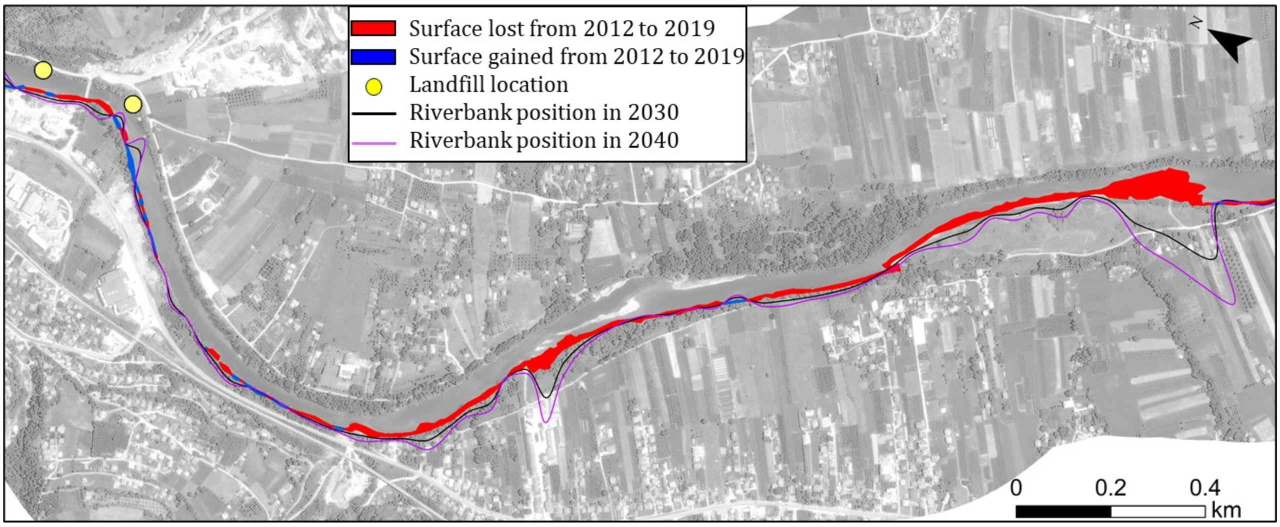


Figure 25 Zoom showing projected riverbank position in 2030 and 2040 near landfill areas

Map Layer id	File Name	Description	Format
[ML.12]	Rightbank_proj_10yr.shp	This is a map layer that contains the projected right riverbank position in 2030.	.shp
[ML.13]	Rightbank_proj_20yr.shp	This is a map layer that contains the projected right riverbank position in 2040.	.shp

Table 10. List of shapefiles providing future location of the riverbanks

3.1.4.4 Potential and limits of VHR image to the environmental harm analysis

3.1.4.4.1 Solid Waste Detection

Main limitation here is linked to the spatial resolution of the image used for detecting wastes. Pleaides data were investigated so far.

This preliminary test shows that floating objects at water surface are easily detectable. Main imitation to proceed with accurate determination if the object origin is related with the input image used. This means that only part of the floating devices (either from natural or anthropogenic origin) cannot be automatically discriminated.

The influence of dumping areas on waste number found in the river is shown. The influence of buried sites seems more important as the one of exposed ones.

This experimentation is promising, VHR orthophotography analysis can be a tool in a near future to derive waste location at the scale of the Lim River and provide information about the most important waste sources.

3.1.4.4.2 Organic/Non-Organic particles in the water column

All in all, the proposed approach appears to be a good tool to detect water quality anomalies along a river. The revisit of Sentinel-2 in the area is very close to the theoretical revisit with up to 10 exploitable images per month in summer and late summer season. This is undoubted the best compromise between satellite revisit and data cost. Yet, very punctual events can be missed out by the satellite, even when an image is available every 2 to 3 days.

Furthermore, most detected anomalies are related to natural events and the few identified suspicious cases are not readily linked to activities in a particular waste site, especially without in-situ knowledge of the area. To reduce over-detection of natural events, the approach could be improved by including a temporal dependency between the SPM values recorded for the same transect and a geographical dependency between adjacent transects. This will enable to filter out anomalies related to long lasting events and to events affecting the river globally.

3.1.4.4.3 Riverbank erosion

The main limit of the analysis is the water level which differs from one date to another, downstream of a dam. Erosion can be confused with a difference in water level linked to forced regulation by the dam.

Luckily, two dates could be compared as the reservoir of the dam was equivalent in 2012 and 2019.

Another limit is the shade generated by the presence of steep gorges. This shade locally prevented the riverbank detection. It differed from one date to another because the time of image acquisition was not the same in 2012 and 2019.

However, very high-resolution is necessary for this type of narrow river and to identify changes in the position of the riverbanks over less than a decade.

The projections are currently limited by the small number of dates analyzed (only two), which does not allow to determine a robust trend considering the variability of the riverbank position. The future projection of the position of the banks is possible: the technique exists. However, a minimum of 4 relatively well distributed dates over the study period should be used for this task.

Despite these limitations, it is entirely feasible to develop a service showing the vulnerability of dumping areas to riverbank erosion hazard, and alerting the authorities about risk of waste discharge at least a few months before accidents occur.

4 TEAM COMPOSITION

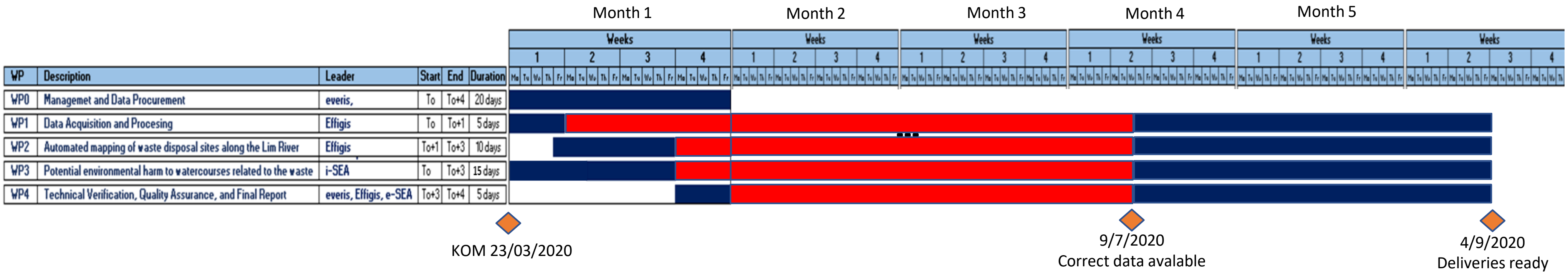
The key personnel involved in the execution of the work is given in table below:

Coordinator		
Patricia Rodriguez Dapena	Project Manager Everis Aeroespacial y Defensa SLU	Management of different tasks of the work order
Contributors		
Yacine Bouroubi	Technical Expert, Effigis	Specialist in methodological development in Earth observation. Supports and guides the Effigis technical team
Pierre Bugnet	Senior Analyst, Effigis	Specialist in image analysis, including object-oriented classification and use of AI techniques
Thuy Nguyen-Xuan	Senior Analyst, Effigis	Environment specialist, responsible for validation of results and performance assessments
Ludovic	Legros	Analyst in data acquisition and pre-processing at Effigis
Virginie Lafon	Manager at i-Sea, Senior Engineer and Senior Researcher	Coordinates the technical leaders in charge of the implementation of service 4. Specialist in methodological development in Earth Observation (e.g. coastline detection, water quality, specialist in aquatic and marine optics). Supports and guides the implementation of the service. Evaluates the outcomes and is responsible for delivering the results
Olivier Regniers	Senior Engineer, in charge of Research and Development at i-Sea	Technical expert and leader of the implementation of services 3. Specilist in aquatic and marine optics in relation with water quality assessment from optical measurements. Performs data processing, analytics and output creation for services 3. Validates and assesses the quality of the final outputs.
Manon Besset	Research Engineer in satellite remote sensing, Researcher in coastal geomorphology	Expert in geomorphology, performed the analysis related to riverbank erosion and further analysis related to riverbank vulnerability to erosion hasard.
Cécile Curti	Marine biologist and GIS expert at i-Sea	Technical expert, in charge of image and GIS analysis. Perfomed the analyses related to waste detection and further analyses related to spatial relation between waste and waste site lication.
Carlos Garcia Daroca	Senior Analyst Everis Aeroespacial y Defensa SLU	Person in charge to develop the software of API with the official geospatial platform of Serbian Re-public Geodetic Authority (RGA).
Pablo Menéndez-Ponte Alonso	Senior Analyst Everis Aeroespacial y Defensa SLU	Person in charge to validation of the outputs according to requirements.

Table 11. Key personnel involved in the project

5 SCHEDULE

Real schedule for the delivery of the services, counting from the release of the Work Order:



The delays were due to input data availability and holiday period to finalise the project after input data was downloaded by project partners.

6 OUTLOOK

UNDP Serbia and the Serbian government will be the main beneficiaries of this project. Extracted data will have a direct impact on the assessment of the current status of legal and illegal dumping sites, infrastructure hazard monitoring, watercourse effluents, and early detection of erosion due to unmanaged waste, etc. They will have a clearer picture of the highlighted problem and a realistic awareness of the situation. Indeed, the produced report will be useful for the government activities of waste management ensuring that Serbia is taking action after the negotiations related to the adhering into the European Union.

If the demonstration in this RFP is successful, it is very likely that the developed methodology can be transferred to other rivers and watercourses in order to get a thorough picture of waste disposal sites in the country. Such information may be used for general consulting purposes and also contribute to the waste management activities and procedures, in particular with those illegal that shall be controlled and penalized.

The following table shows a list of possible stakeholders and final users of the services that can be involved in the final outcomes of this project.

Users and Stakeholders	Sector	Website
Ministry of Economy of the Republic of Serbian	Finance Resources	https://privreda.gov.rs/english/
Ministry of Environmental Protection of Serbian	Sustainable Environment Management	https://www.ekologija.gov.rs/en
Ministry of Agriculture, Forestry and Water Management of Serbian	Forestry and Water Management.	http://www.mpn.gov.rs/en
UNDP for Serbian	Sustainable Development	https://www.rs.undp.org/
Ministry of Environmental of Federation of Bosnia and Herzegovina	Sustainable Environment Management	http://www.fbihvlada.gov.ba/english/ministarstva/okolis_turizam.php
Ministry of Environmental of Montenegro	Sustainable Environment Management	http://www.mrt.gov.me/en/ministry?alphabet=lat
UNDP Accelerator Labs	Innovation	http://www.nature-ic.am/en/aboutus
Serbian Republic Geodetic Authority	Republic Geodetic Authority	https://eurogeographics.org/member/republic-geodetic-authority/
European Space Agency	Aerospace	https://eo4society.esa.int/eo_clinic/

Table 12. Final Users and Potential Stakeholders

Finally, if the service is deployed, dissemination activities and workshops with the end-customers will be held, to maximize the impact of the project and to create awareness of the use of geospatial data.

6.1.1.1 Potential and limitations of the technique to detect waste sites

Although the time and budget available for the project was exploited to the maximum extent, limited success has been obtained for the mapping of waste disposal sites using Very High Resolution (VHR) satellite imagery and a deep learning classifier. Several factors may explain this.

Given the need for producing a representative map showing the distribution of waste disposal sites for a country such as Serbia in an automated and cost-effective manner, a certain number of factors would help improve the results obtained in this first, exploratory study:

- The resolution of input imagery should be increased from 50 cm to 20 cm if and when recent aerial photography is available and if not, at least to 30 cm by acquiring WorldView-3 and -4 imagery (please note that **everis has a DigitalGLobe/Maxar GBBDX license and special prices for images from Maxar as being in partnership for supporting Maxar in Europe)**.
- More imagery and more resolution will imply more storage and computing IT requirements.
- More time should be allowed to test with other AI algorithms/approaches and tweak their parameters (window size, etc.).
- Additional methodological steps should be incorporated such as thresholding to take into account, for instance, the distance between waste sites and roads. In other words, pre-processing that would eliminate all non-vegetated objects located far from roads (≥ 30 m from a road) could help reduce the number of false alarms (commission errors). This process would be facilitated by having access to an up-to-date road layer from Government authorities.
- The number of training sites should be increased, when possible, for all types of waste sites. As it appears in this case that buried, levelled and industrial waste sites are relatively uncommon, focus should probably be placed on only one type, that is ''exposed waste sites''.
- The impact of using a different data set for training (40-cm aerial photography resampled to 50 cm) and for the actual classification (50-cm Pléiades) needs to be assessed as this may affect to some extent the results of the classification. Ideally, the same data should be used for both the training and the information extraction/mapping process.

APPENDIX A: REFERENCES

The following table shows references of our consortium which apply to the current RFP:

Company		
Effigis	Detection of sick and dying trees using artificial intelligence algorithms (2019) – Hydro-Québec	Development of an automated method to identify trees that threaten electric power lines using very high-resolution satellite imagery (Pléiades) and AI algorithms. The success of the methodology led to Effigis being awarded another contract by Hydro-Québec in a different type of environment. Pierre Bugnet developed the methodology and the results were validated by Thuy Nguyen-Xuan.
	Assessment of technical rooftop solar PV potential in Vietnam using satellite imagery and AI techniques (2017-2018)– World Bank Call for Proposals	Development of a methodology to automatically characterize rooftops in two Vietnamese cities (Ho Chi Minh City and Da Nang (close to 2 M rooftops in total) with respect to their potential for the installation of solar panels. AI algorithms were used to identify, delineate and characterize rooftops (contours, shape, orientation, etc.) from very high resolution WorldView-3 imagery (30 cm). Yacine Bouroubi was the PI of the project, with Pierre Bugnet as image analyst and Thuy Nguyen-Xuan as GIS analyst.
	Detection of artisanal mining sites in Burkina Faso (2018-2019) – ANEEMAS (national agency in charge of monitoring artisanal mining sites in Burkina Faso)	Very high-resolution satellite imagery (available on GoogleEarth) was used to detect artisanal mining sites. Object-oriented classification was used to detect potential sites, which were validated in the field, followed by the production of a geodatabase of artisanal mining sites over the entire country. Pierre Bugnet acted as image analyst and Thuy Nguyen-Xuan as GIS analyst for this project.
	Mapping of individual trees – Since 2008 on a recurring basis – CAE (major provider of flight simulators)	Developed an automated extraction method based on object-oriented classification of the tree crowns in the vicinity of airports using very high resolution (30 and 50-cm) satellite imagery. Over the past 2 years, AI-based algorithms are used to better identify tree crowns. Pierre Bugnet developed the methodology.
i-SEA	Space for Shore project (2019) – ESA Coastal Erosion Tender	Development of a European Service for the characterization of Coastal erosion and shoreline monitoring based on space imagery. Prototyping R&D, large scale demonstration in 5 pilot countries (France, Germany, Portugal, Greece, Romania) cover 8 European regions. I-Sea is the Consortium Leader, Virginie Lafon is the PI of the project.
	HAB RISK (2018-2019) – Risk of Harmful Algal Bloom (CMEMS User Uptake)	Demonstration of an operational service for Harmful Algal Bloom monitoring and forecasting over the Baltic Sea. Implementation of the service over a web platform (Rheticus® Planetek Italia) and mobile interfaces. I-Sea is the Consortium Leader, Virginie Lafon is the PI of the project.
	Monitoring and forescasting seagrass Sargassum drift in the Caribbean region from satellite remote sensing and modelling (2018: DREAL Guadeloupe-2019: Météo-France / CLS)	Weekly surveillance of Sargassum presence over the in a 1000 km x1000 km area in the Atlantic Ocean / Caribbean using MR/HR satellite timeseries (VIIRS/MODIS/Sentinel-3/Sentinel-2). Development of Machine learning techniques for Sargassum retrieval based on Séntinel-2 imagery. Forecasting of daily Sargassum drift using CMEMS ocean models.
	Mapping wild oysters and farms using Deep learning approaches (2019 – 2020: Agence Française pour la Biodiversité)	Development of Deep Learning approach to characterize the wild oysters and oysters' cultures at large scale, based on very-high resolution imagery.
	Vegetation mapping over various sites in France (13 commercial contracts over the past 5 years + 2 R&D projects)	Mapping of natural coastal/estuarine/lagoon/terrestrial habitats and ecosystems, specific species (including estimation of vegetation cover), of based on Deep and Multi-temporal Machine learning techniques.

Company		
	Estuarine & Coastal Water quality monitoring (10 commercial contracts over the past five years + 1 R&D project)	Mapping turbidity from medium to high resolution optical data. Provision long-term database and expert analysis on time and space evolution of the turbidity at short, medium and long-time scales. Objectives: scientific description of the turbid climates and evaluation of potential impact of works on vulnerable ecosystems.
everis	Moverick – Infrastructure Management integrated solution	Moverick is everis Ingenieria's own development for the complete and integrated management of operational infrastructures. Geospatial information is used for planning, real-time management, calculations and final users' information.
	DOMUS Consortium – Drones aerial traffic management	GIS for drones' aerial traffic management restrictions based on meteorology, geo-fences, GNSS signal quality, NOTAMS, etc. Centralized cartographic repository development, accessible from several functional modules from DOMUS Consortium. Multiple sources for data acquisition driven by automatic processes. Complete solution based on Open Source standards.
	DREEAM Tool – Energetic efficiency calculator	DREEAM is a tool developed by an international consortium designed to calculate and manage the energetic efficiency on buildings. It uses geospatial information to obtain data about the weather, sun hours, building orientation, shadows, and other influential parameters.
	Agriculture Ministry Spain (MAPA) – Corporate GIS	Corporate Geographic Information System for the Agriculture, Fish and Food Ministry (MAPAMA), by unifying many GIS technologies and implementations from different departments in a single centralized server for services and cartography. Electronic Water Registry to manage inscriptions and setups.

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APPENDIX C: LIST OF ACRONYMS

Acronym	Meaning
ADB	Asian Development Bank
AOI	Area of interest
DEM	Digital Elevation Model
EO	Earth Observation
ESA	European Space Agency
HTML	HyperText Markup Language
KARM	Kazakhstan Resident Mission
KoM	Kick off meeting
KSTA	Knowledge and Support Technical Assistance
ML	Map Layer
PDF	Portable Document Format
PNG	Portable Network Graphics
RFP	Request for Proposal
RGA	Republic Geodetic Authority
ROI	Region of Interest
SEPA	Serbian Environmental Protection Agency
SPM	Suspended Particulate Matter
SRTM	Shuttle Radar Topography Mission
UNESCO	United Nations Educational, Scientific and Cultural Organizations
URL	Uniform Resource Locator
WMS	Web Map Services
WMTS	Web Map Tiled Services
WO	Work Order
WOR	Work Order Report
WP	Work Package

Table 14. List of Acronyms

APPENDIX D: WASTE DISPOSAL SITE TYPE INTERPRTATION GUIDE

Characterization of waste sites along the Lim River in Serbia

Interpretation guide

Prepared by:

Effigis GeoTechnologies

September 2020

1 CONTEXT AND OBJECTIVE

This interpretation guide was developed as part of a project that aimed to locate and characterize waste sites along the Lim River through the use of remotely sensed imagery. The detection of the waste site is to be performed with image analysis algorithms based on artificial intelligence.

The objective of the interpretation guide is to establish a common understanding, between the developers of the methodology and the clients, of the description and characterization of the waste sites to be located. This should facilitate the selection of the training and validation sites needed for the development of the detection algorithm and should ensure that the maps produced meet the needs of the client.

2 DEP2 INVENTORY

In order to have a first understanding of the characteristics of the elements to be detected, we asked if there existed a recent inventory of waste disposal sites in the study area. UNDP-Serbia sent us a file listing 22 illegal landfill sites and documenting their location (location, municipality, geographic coordinates) and their size:

- DEP2_specification_of_illegal_landfills.xls

Using the provided geographic coordinates, we georeferenced the 22 sites and visually examined them in Google Earth. For the majority of the sites, the most recent background imagery consisted of a very high resolution (VHR) satellite image acquired on 2019-08-05.

2.1 Confirmed illegal waste disposal sites

From the 22 visually examined sites, five were easily recognised as active waste disposal sites (Figure D.1). Their characteristics include:

- Presence of light coloured (white) waste
- Speckled/spotted appearance of waste heaps
- Waste heaps located in open area, often a mineral surface
- Waste disposal site is usually located near a road (on the side or at the end of the road)
- Size of waste disposal site is variable (from 100 m² to 2000 m²)

Brodarevo (Prijepolje)
43.221700; 19.735800
Reported area: 80 m², interpreted area: 1,795 m²

Brodarevo (Prijepolje)
43.220900; 19.728400
Reported area: 50 m², interpreted area: 176 m²

Prijepolje (Prijepolje)
43.385000; 19.637300
Reported area: 70 m², interpreted area: 110 m²

Milesevo (Prijepolje)
43.371400; 19.691700
Reported area: 100 m², interpreted area: 308 m²

Mijoska (Prijepolje)
43.348900; 19.637400
Reported area: 50 m², interpreted area: 223 m²

Figure D.1 Illustration of visually confirmed waste disposal sites from DEP2 inventory. Background image: 2019-08-05

2.2 Possible illegal waste disposal sites

From the 22 visually examined sites, six were recognised with a great deal of uncertainty as waste disposal sites (Figure D.2). Compared to the confirmed sites, the uncertain sites still had a speckled/spotted (or bumpy) appearance but were darker in color. They were also located in open areas but generally with a vegetated surface rather than mineral. Like the confirmed sites, they were usually located near a road. The majority of the sites were of smaller size (100 m² to 200 m²).

Prijepolje (Prijepolje)
43.364900; 19.624100
Reported area: 200 m², interpreted area: 187 m²

Prijepolje (Prijepolje)
43.361700; 19.618600
Reported area: 100 m², interpreted area: 181 m²

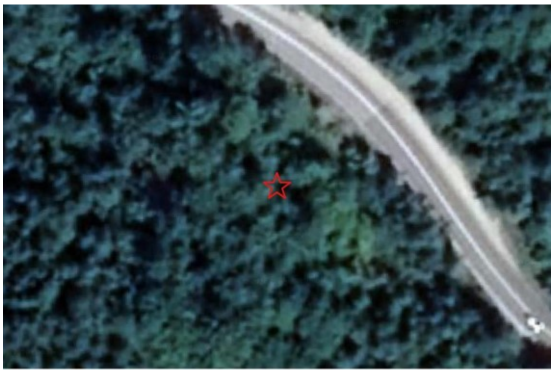
Milesevo (Prijepolje)
43.370900; 19.691100
Reported area: 80 m², interpreted area: 113 m²

Banja (Priboj)
43.534235; 19.577187
Reported area: 80 m², interpreted area: 1,219 m²

Figure D.2 Illustration of possible waste disposal sites from DEP2 inventory

2.3 Unconfirmed illegal waste disposal sites

There was no visual confirmation for 11 of the 22 examined sites. For these sites, no evidence of waste could be observed on the examined images. In some cases, the located site corresponded to a forested area (Figure D.3). If present, the waste would be located under the tree cover and would therefore not be visible.



Jabuka (Prijepolje)
43.330300; 19.537300
Reported area: 50 m²

Seljasnica (Prijepolje)
43.373700; 19.596200
Reported area: 100 m²

Figure D.3 Illustration of possible presence of tree cover over waste disposal site

In some other cases, the located site corresponded to an open area, but no evidence of the presence of waste was visible on the examined image (Figure D.4). It might be possible that, at the date of observation (2019-08-05), the waste had been removed.

Brodarevo (Prijepolje)
43.220800; 19.729600
Reported area: 150 m²

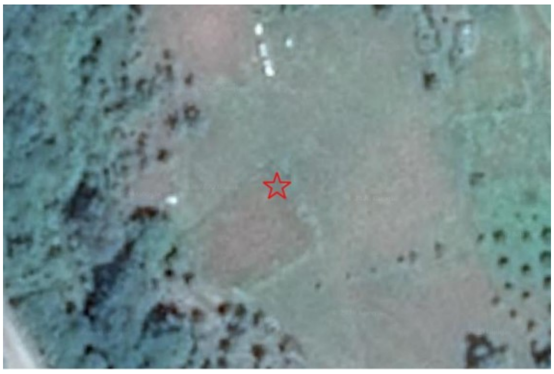
Gracanica (Prijepolje)
43.318900; 19.677300
Reported area: 50 m²

Figure D.4 Illustration of site where waste was possibly removed

Finally, in some cases the absence of visible evidence of waste might be explained by the date of the image examined. Figure D.5 illustrates two sites where the image available for viewing in Google Earth was from 2017-07-05. It is possible that the waste disposal activity on these sites began after that date.

The examination of the recent inventory (DEP2) allowed for a first understanding of the characterization of illegal waste sites. However, the small number of confirmed sites does not allow for a comprehensive look at the variety of situations that can be observed. For this reason, we performed the same exercise with another inventory that contained a far greater number of sites.

Sjeverin (Priboj)
43.602356; 19.378194
Reported area: 110 m²



Hercegovacka Golesa (Priboj)
43.549182; 19.427204
Reported area: 120 m²

Figure D.5 Illustration of sites where waste possibly appeared after date of imagery viewed

3 SEPA INVENTORY

We retrieved a second inventory of waste disposal sites from the SEPA website (http://www.sepa.gov.rs/index.php?menu=207&id=1007&akcija=showExternal&Lang=Latinica):

- Mapa_starih_i_divljih_deponija_u_Republici_Srbiji.kmz

This kmz file provides the location of more than 3,500 waste disposal sites (about 150 legal and 3,350 illegal) throughout Serbia. Although no specific date is indicated for the inventory of the sites, we believed that it corresponds to the one referred to by Stanisavljenic et al. in their 2012 study on methane emissions from landfills in Serbia. We therefore assigned a date of circa 2012 to this inventory.

As with the previous inventory (DEP2), we visually examined the sites contained in this inventory in Google Earth using the tool allowing the viewing of archive VHR imagery (spanning from 2000 to 2019 depending on the region). We generally viewed images that dated from 2011 to 2014. Out of the 3,500 waste disposal sites contained in the SEPA 2012 inventory, a total of 165 were visually examined in Google Earth. Out of those 165 sites, 67 (41%) were visually confirmed. For the remainder of the examined sites (98 sites), we observed situations similar to those described for the DEP2 inventory: uncertain recognition of waste, open area but no waste visible, or forested area.

3.1 Sites with visible waste

The confirmed sites had visual characteristics similar to those described in section 2.1. Figure D.6 provides some examples of sites with visible waste. They are similar in appearance and as variable in size as the ones confirmed in the DEP2 inventory.

Novo Naselje (Priboj)
19.539255; 43.551311
Date: 2013-09-25, Interpreted area: 183 m^2

Vucak (Smederevo)
20.920876; 44.611737
Date: 2014-04-02, Interpreted area: 358 m^2

Krupanj (Krupanj)
19.332652; 44.401934
Date: 2013-08-18, Interpreted area: 2030 m^2

Lipe (Smederevo)
21.023283; 44.637037
Date: 2013-10-23, Interpreted area: 1848 m^2

Figure D.6 Illustration of sites with visible waste

3.2 Sites with dark mounds

In visually confirmed waste disposal sites, the waste heaps was usually light (white) coloured (Figure D.1 and Figure D.6). In some of the examined waste disposal sites from the 2012 inventory, we also observed some dark coloured mounds (Figure D.7). We interpreted them as waste heaps covered by a layer of soil and/or as soil mounds used for burying the waste. This secondary intervention (i.e. burial of the waste) would indicate some kind of minimal level of management of the waste disposal site.

Nova Varos (Nova Varos)
19.795417; 43.459183
Date: 2013-09-25, Interpreted area: 2,567 m^2

Bogojevici (Arilje)
20.118963; 43.722879
Date: 2014-03-14, Interpreted area: 2,843 m^2

Snejica (Snejica)
19.983774; 43.289186
Date: 2013-08-12, Interpreted area: 2,803 m^2

Snejica (Snejica)
19.983774; 43.289186
Date: 2014-02-24, Interpreted area: 2,803 m^2

Figure D.7 Illustration of sites with visible waste

3.3 Sites with leveling of waste

Many of the municipal (legal) waste disposal sites contained in the 2012 inventory showed some greater level of management through the observation of the levelling of and burial waste heaps, sometimes in multilayered terraces (Figure 8). Over time, these levelled waste sites can even develop some vegetation cover.

Bajina Basta (Bajina Basta)
19.565522; 43.998461
Date: 2013-10-22, Interpreted area: 19,490 m^2

Loznica (Loznica)
19.194125; 44.540585
Date: 2011-09-23, Interpreted area: 9,070 m^2

Loznica (Loznica)
19.194125; 44.540585
Date: 2012-10-21, Interpreted area: 9,070 m^2

Loznica (Loznica)
19.194125; 44.540585
Date: 2013-10-21, Interpreted area: 9,070 m^2

Figure D.8 Illustration of sites with visible waste

Out of the visually confirmed waste disposal sites from the 2012 inventory, 69 % consisted of sites with visible waste, 18 % were sites with dark mounds, and 9 % were sites with leveled waste.

4 2019 VISUAL INVENTORY AND TYPES OF WASTE SITES

Pleiades satellite imagery covering the Lim River area of interest (92.5 km² – 500 m buffer from shoreline) was purchased. The Pleaides images have a resolution of 50 cm and were acquired on 2019-08-06, 2019-07-04 and 2018-11-06. A visual inspection of the imagery was carried in order to make an inventory of the waste disposal sites present over the entire AOI. The waste sites observed were attributed one of the following three classes, based on the types of sites observed in the DEP2 and SEPA 2012 inventories discussed previously:

1. Exposed waste
2. Buried waste
3. Leveled waste

Examples of these classes are provided in Figure D.9.

Exposed waste

Buried waste

Figure D.9 Illustration of waste sites classes

The visual inspection of the AOI also allowed us to recognize a possible fourth class:

4. Industrial waste

Examples of this class are illustrated in Figure 10 (upper). However, this new class might not be easily be distinguished from commercial yards (Figure 10 lower).

In all, over the entire AOI, the 2019 visual inventory yielded: 16 exposed waste sites, 14 buried waste sites, and seven industrial sites. No leveled waste sites were observed. However, about 30 more sites were considered uncertain.

Industrial waste

Industrial waste

Commercial yard

Commercial yard

Figure D.10 Illustration of industrial waste sites (above) and commercial yard sites (below)

We have joined a cartographic layer to this document:

- UNDP_Serbia_Lim_River_2019_inventory.shp

It can be viewed overlying the 2019 Pleiades orthomosaic produced for this project. It contains the 67 sites identified in the 2019 visual inventory. We also joined a version of it in a KML format than can be viewed in Google Earth. It can be shared with UNDP-Serbia / SEPA so that it can serve as a basis for discussion of the types (classes) of waste disposal sites to be used for the training of the detection algorithm and the cartographic data to be produced. This discussion should lead to the confirmation of the proposed site types and the validation or removal of the uncertain sites from the inventory.

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